MONTREAL PROTOCOL
ON SUBSTANCES THAT DEPLETE
THE OZONE LAYER

UNEP

1994 Report of the
Methyl Bromide
Technical Options Committee

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pursuant to
Article 6
of the Montreal Protocol;
Decision IV/13 (1993)
by the Parties to the Montreal Protocol

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EXECUTIVE SUMMARY

1. Committee Mandate

The Methyl Bromide Technical Options Committee (MBTOC) was established by the Parties to the Protocol to review technical issues concerning methyl bromide, the material listed in Annex E of the Protocol.

MBTOC, and this report in particular, address the technical availability of chemical and non-chemical alternatives for the current uses of methyl bromide, apart from its use as a chemical feedstock. It covers the methodologies to control emissions of methyl bromide into the atmosphere, potential for recovery, reclamation and recycling and the issues of special relevance to Parties operating under Article 5. It also provides an estimate of emissions to the atmosphere from present uses.

The Committee currently consists of 68 members, with representation from 23 countries drawn from a wide range of expertise and interests associated with methyl bromide, including scientists, end users, manufacturers, NGOs, and government representatives from Parties including 8 from Article 5 countries.

2. Existing uses of methyl bromide

Methyl bromide is principally used as a fumigant, controlling a wide spectrum of pests, including pathogens, insects and nematodes. It has sufficient phytotoxicity to control many weeds and seeds in soils.

It has features which make it a versatile and convenient material with a wide range of applications. In particular, it is quite penetrative, usually effective at low concentrations and leaves residues which have generally been found acceptable. Its action is usually sufficiently fast and it airs rapidly enough from treated systems to cause relatively little disruption to commerce or crop production.

Methyl bromide is normally supplied and transported as a liquid in pressurised cylinders but at ambient temperature and pressure, the material is a gas. These containers are typically cylinders of about 10 to 200 kg in content, though there is also trade in larger containers and also small pressurised disposable steel cans typically of 0.5 to 1 kg capacity each. Methyl bromide is normally used directly from these cylinders or containers, but may sometimes be transferred to smaller units.

Of the 1992 global sale of methyl bromide of 75,625 tonnes, 3.2% was used as a feedstock for chemical synthesis. It is estimated that the remainder was used for soil treatment (76%), fumigation of durables (13%), fumigation of perishables (8.6%), and fumigation of structures and transportation (3.0%). The proportions for 1991, the base year, are similar to those for 1992. The Committee noted that, in the absence of controls, some developing countries expect to expand uses of methyl bromide substantially. Global consumption, excluding feedstock uses, has increased about 3700 tonnes per year since 1984.

Although methyl bromide is clearly a most useful tool in specific instances, there are a number of issues not related to the ozone depletion, which have led countries to impose restrictions on its use. Concerns include toxicity to humans and associated operator safety and public health, and residues. In some countries, pollution of surface and ground water by methyl bromide and derived bromide ion is also of concern.

3. Emissions from methyl bromide use, and their reduction, including recovery

Estimates of the proportion of methyl bromide released into the atmosphere vary widely. Emissions occur inadvertantly through leakage and permeation during treatment and intentionally while venting at the end of treatments. The quantity of methyl bromide emitted from a treatment varies on an individual case basis as a result of the use pattern, the condition and nature of the fumigated materials, the degree of seal of the enclosure, and local environmental conditions. Methyl bromide is a reactive material: it is incorrect to equate production with emissions as at least part of methyl bromide applied is converted in use to non-volatile materials.

Under current usage patterns, the proportions of applied methyl bromide emitted eventually to atmosphere globally were estimated by MBTOC to be 30 - 85%, 51 - 88%, 85 - 95% and 90 - 95% of applied dosage for soil, durables, perishables and structural treatments, respectively. These figures, weighted for proportion of use and particular treatments, correspond to a range of 46 - 81% overall emission from agricultural and related uses (34,000 - 59,000 tonnes, based on 1992 sales data).

Available containment techniques for decreasing methyl bromide leakage are in limited use worldwide. Lack of adoption is constrained particularly by poor dissemination of information and perceived or real increases in costs and logistical problems. A high degree of containment is a prerequisite for efficient recovery of the used methyl bromide.

Better sealing of enclosures and the use of less permeable sheeting were identified as an immediately applicable, technically proven means of reducing emissions from soil, durable commodity and structural fumigations, with the largest improvement coming from soil fumigation. These measures, combined with longer exposure times, may permit reduced dosage levels while still achieving the required degree of pest control. Many facilities used for fumigating perishables, particularly for quarantine, already have a high standard of gastightness, leading to very low leakage rates (often less than 2% of dosage).

There is active research into the development of recovery and recycling equipment for methyl bromide. A few special examples of recovery equipment are in use and it is anticipated that prototype systems capable of recycling recaptured gas for some use areas will be evaluated by the end of 1995. Most development work is directed at recovery from enclosures used for structure or commodity fumigation (about 22% of global non-feedstock production). Some preliminary work on recovery for soil fumigation is in progress.

It is unlikely that significant demand from developing countries can be met with recycled material. There is, however, potential for some recycling in some specialised applications, including in Article 5 countries, when commodities, notably perishables, are treated in gastight chambers.

Most of the potential recovery and recycling systems are complex and may be expensive to install compared with the cost of the fumigation facility itself. Some systems would have high running costs associated with energy requirements. Many would require a level of technical competence to operate that would not normally be found at many fumigation facilities.

If recovery is to be recognised as an acceptable method of reducing methyl bromide emissions to the atmosphere, it will be necessary to set specifications on aspects of fumigation, such as equipment efficiency and tolerable levels for emission.

4. Alternatives to methyl bromide

There is no single alternative to methyl bromide in all of its wide range of uses. However, technically, alternatives do already exist for a number of current applications.

A number of potential alternative chemicals have been identified. They include fumigants and non-fumigants. However, the environment and health considerations, which may limit the use of any pesticide, including methyl bromide, need to be taken into account when selecting alternatives. Furthermore, it is very likely that regulatory restrictions on use of agrochemicals will increase, resulting in higher costs of use and increasing inconvenience. Additionally, costs of achieving full commercial registration of unregistered materials are high, and the process is slow. It was noted that there are specific constraints on rapid implementation of some alternatives associated with the time taken to gain registration and regulatory acceptance of some procedures. The problem is particularly acute in some cases relating to treatment of exports to meet quarantine standards where extensive trials and protracted bilateral negotiations may be required.

Many of the alternatives identified by MBTOC were of the 'not-in-kind' type. In a number of cases a rational combination of procedures, including non-chemical measures, can be used to avoid creating the circumstances where methyl bromide is currently regarded as irreplaceable. This approach, known as Integrated Pest Management (IPM), utilises pest monitoring techniques, establishment of pest injury thresholds, and a mix of tactics selected to prevent or manage pest problems. Emphasis is placed on producing a marketable crop using safe, environmentally sound and cost-effective procedures. Chemical intervention, at present possibly including use of methyl bromide, is employed only on the basis of need rather than by routine. The ability to design IPM depends on a thorough knowledge of the pest or disease complex to be controlled.

In general, the effect on production and profitability will vary widely and may lead to increases, or decreases, depending on local circumstances. In the only instance of methyl bromide phaseout for soil fumigation throughout a country (the Netherlands) it is reported that adoption of some alternatives have increased yields in specific crops.

MBTOC estimates that by using known technology it is technically possible for Parties operating under Article 2 to significantly reduce usage of methyl bromide. Estimates of the magnitude of the reduction and its time scale varied widely amongst MBTOC members. Opinions ranged from a reduction of 50% feasible by 1998, to decreases of only a few percent by 2001. Reductions should be achievable through a combination of implementing alternatives and use of better containment technology, together with longer exposure times and lower dosages for methyl bromide treatment, particularly in soil fumigation. Achievement of such reductions may entail use of some alternatives which may have potential to cause adverse environmental and health effects. Some alternatives, notably those leading to residues in products, while technically effective, may not be acceptable to regulatory authorities, markets or end users.

MBTOC did not identify a technically feasible alternative, either currently available or at an advanced stage of development, for less than 10% of 1991 methyl bromide use. These include control of some soilborne viruses and other pathogens and some quarantine procedures.

MBTOC assumed that the most energy intensive alternative to methyl bromide was use of steam heating for soil treatment. The indirect Global Warming Potential of methyl bromide, in terms of CO_2 produced, with energy required supplied electrically, was 20 kg CO_2 per tonne for synthesis and vaporisation. Using equivalent energy sources, steaming at 4 - 7 m^3 per m^2 and methyl bromide at 25 - 100 g per m^2 were equivalent to 1200 - 2100 and 5 - 20 g CO_2 per m^2. The atmospheric lifetimes of all gaseous potential alternatives to methyl bromide were too short to give appreciable direct GWP.

4.1. Alternatives on a sector basis

4.1.1 Soils

On a global basis, the largest single use of methyl bromide is as a soil fumigant (about 75% of non-feedstock uses). It is used as a preplant soil fumigant to maintain or enhance crop productivity in locations where a broad complex of soilborne pests, including diseases, limit economic production of certain crops, and particularly where they are repeatedly grown on the same land. Methyl bromide has been successfully used under a wide variety of cropping systems. The major current categories of use include some nursery crops, vegetables, fruits, ornamentals and tobacco.

Soil fumigation with methyl bromide has been successfully replaced in diverse areas by methods and techniques that have been available for many years, by adapting or modifying them to suit local requirements. None of the specific alternative methods discussed, except steam, when used alone, have the broad spectrum of activity, efficacy or consistency of methyl bromide. For some situations there may not be existing alternatives for methyl bromide. The development of a comparable agricultural system without the use of methyl bromide, in many cases, may require the integration of multiple alternative techniques (IPM). A commitment to research and technology transfer will be required to achieve a similar spectrum of efficacy and reliability, and adoption by growers.

An IPM approach to managing pests and diseases will be needed in order to avoid future environmental problems associated with soilborne pest control. Each individual tactic in an IPM strategy may have constraints, but the package of approaches can often be tailored to specific sites and situations to provide effective pest management. In this context, constraints should be viewed as indicating research gaps. Research to overcome these constraints needs to focus not only on biophysical systems, but also socio-economic and political parameters, and generation of registration data.

A number of non-chemical alternatives are currently in use and other potential alternatives are under investigation. These are not equally effective for all pests, cropping systems or locations and may have a narrow spectrum of activity. Non-chemical alternatives include:

- Cultural practices such as crop rotation, planting time, artificial plant growth substrates, deep ploughing, flooding/water management, fallowing, cover crops, living mulches, fertilization/plant nutrition, and plant breeding and grafting.
- Biological control and organic amendments
- Physical methods such as soil solarization, steam treatments, superheated or hot water treatments and wavelength-selective plastic mulches.

Non-chemical alternatives generally do not require extensive regulatory approval.

There are a number of available and potential replacement fumigants, including methylisothiocyanate (MITC), compounds which generate MITC, and halogenated hydrocarbons. Mixtures of soil fumigants may provide a spectrum of control approaching that of methyl bromide. These combination products may represent the most efficacious short-term alternatives to methyl bromide in certain situations, provided they are acceptable to regulatory agencies.

Control of individual soilborne pests and diseases approximating that of methyl bromide may be achieved in some cases through the use of combinations of non-fumigant materials (e.g. nematicides, fungicides, herbicides and insecticides).

There are additional chemicals which would require further research to determine their potential as alternatives for methyl bromide. Some were previously used with varying degrees of success (e.g. anhydrous ammonia, formaldehyde, carbon bisulphide, inorganic azides). Renewed interest and research may lead to re-establishment of some of these pesticides.

4.1.2 Durables

Durables include dry agricultural and forestry products, such as cereal grains, dried fruits and nuts, timber and artifacts. Approximately 13% of non-feedstock global production of methyl bromide is used for disinfestation of durable commodities. Generally, methyl bromide is not widely used on durables but a few economically important industries have a tradition of use of methyl bromide fumigation as their principal means of pest control. These include the dried fruit and nut industry, some major importers and exporters of cereal grains, and export trade in unsawn timber. Methyl bromide is particularly useful where a rapid treatment is needed, such as at import or prior to shipment, and for quarantine purposes. It is effective down to low commodity temperatures (5°C).

There are potential or existing alternatives for most uses of methyl bromide on durable commodities. However, there is no general in-kind replacement. All alternatives will require some changes in practice. Of the alternatives, only phosphine is extensively used, principally for cereals and legumes. Insect resistance to phosphine is an emerging problem, particularly in developing countries, but resistant pests can, at present, be controlled using currently used phosphine-based technology.

Some alternatives are already in industrial use for some classes of durable. Those identified include other fumigants, controlled and modified atmospheres, contact insecticides, physical methods and biological control methods. Many are limited in particular circumstances by speed of action, regulatory constraints, temperature, consumer acceptance, and lack of research data.

4.1.3 Perishables

Perishable commodities include fresh fruits and vegetables, cut flowers, ornamental plants, fresh root crops and bulbs. Methyl bromide fumigation is the predominant treatment when disinfestation is required for perishable commodities, using about 8.6% of global non-feedstock methyl bromide production, with about half of that for disinfestation of fruit for quarantine purposes. A minor quantity of methyl bromide, less than 0.2% of global use, is used to help prevent the spread of pests within countries.

Alternative treatments to methyl bromide include pest-free zones, inspection, physical removal, the systems approach; and disinfestation based on chemical treatments, coldstorage, heat, controlled and modified atmospheres, irradiation and a combination of these treatments. Although these are approved for disinfestation of specific commodities, very few are in use relative to the number of different commodities treated with methyl bromide. Their widespread application is limited in some cases by their commodity and pest specificity. There are also very few examples of alternative treatments developed for commodities routinely treated with methyl bromide because few people recognised the need to develop them until now.

For each alternative, MBTOC identified a number of specific approvals in various countries. For example, heat treatments are approved for 6 applications, chemical fumigants for 5, cold treatments for nine, pest-free zones for four, and irradiation for two. Currently, there are no existing alternatives, meeting quarantine standards, for five groups of economically important exports: apples and pears infested with codling moth; stonefruit infested with codling moth; grapes potentially infested with a certain mite (from Chile to the USA); berryfruit infested with various insects; and certain root vegetables where soil is not removed.

Some promising alternatives require further research to determine their suitability for control of pests in specific commodities. MBTOC identified twelve potential alternative treatments.

MBTOC noted that there are constraints on use of chemical treatments for disinfestation of perishables and that they have very limited application. They are difficult to apply, have a narrow pest spectrum of activity, can damage many commodities, and are not approved for use in some countries. Many consumers have indicated preference for foods with less or without chemical residues, provided they are of good quality and value.

Perishable commodities absorb relatively little methyl bromide, leaving 85 - 95% available for recovery. Many perishable commodity fumigations are carried out using well-sealed solid-wall facilities, that restrict leakage. There is thus opportunity for efficient recovering and recycling. Where alternatives are not feasible for quarantine treatments, minimising methyl bromide released using recapture technology could be used to maintain national and international trade in perishables.

4.1.4 Structures and transportation vehicles

Treatment of structures and transport vehicles uses about 3.0% of global non-feedstock methyl bromide production.

Fumigation is used as a structural pest management technique on either an entire structure or a significant portion of a structure. It is utilized whenever the infestation is so widespread that localized treatments may result in reinfestation or when the infestation is within the walls or other inaccessible areas.

Structures that are fumigated are classified as food production and storage facilities (mills, food processing, distribution warehouses); nonfood facilities (dwellings, museums), and transport vehicles (trucks, ships, aircraft, railcars).

Pest management in these facilities is best achieved through IPM procedures. These may include periodic full site treatments. Reduction or elimination of the use of methyl bromide can be accomplished with IPM programs in some situations, including some full site treatments. Structural IPM relies on good construction and maintenance with modification, where required, to remove pest harbourages, and sanitation to remove pests and their food sources. Pest detection serves as a quality assurance for the pest management program, and indicator of need for treatment.

There are significant opportunities to reduce methyl bromide dosage through better containment and monitoring, and combining methyl bromide with carbon dioxide.

Presently, there is no single substitute fumigant for methyl bromide for all treatments of structures against pest infestation. Phosphine and hydrogen cyanide are alternative fumigants in some situations, including full site treatments. Sulphuryl fluoride is used as a direct substitute for methyl bromide to eradicate wood destroying insects in some countries. Non-fumigant pesticides and non-chemical methods are also being used as local treatments. Heat treatment is probably the most useful non-chemical fullsite technique. Other alternative pest management strategies incorporate the use of non-fumigant pesticides and non-chemical procedures.

Transport vehicles pose particularly difficult pest management problems because they often contain sensitive equipment, innumerable harborages and it is economically difficult to keep them out of operation for more than a brief period. Furthermore, methyl bromide is the only fumigant currently allowed for quarantine treatments on ships in many countries. Presently there are no established alternatives to methyl bromide for rapid rodent and insect elimination aboard aircraft.

5. Concerns relating to Article 5 countries

Developing countries currently use about 18% of methyl bromide produced globally for agricultural and related uses. The main uses are for soil fumigation (about 70% of total) and disinfestation of durables (about 20%).

Soil fumigation is mainly carried out in Article 5 countries for pest and disease control in the production of certain high value cash crops (e.g., tobacco, cut flowers, strawberries, vegetables). It is used particularly for fumigation of nursery and seed beds. Methyl bromide is not used during production of staple foodstuffs. Where used on durables, the main application is the protection of local stocks of food grains and for disinfestation of imported and exported cereal grains. Some perishables, important to particular economies, are fumigated on export to developed countries.

Alternatives to methyl bromide in developing countries and potential constraints on their use are the same as in developed countries, but some chemical treatments, not permitted in some developed countries, may still be acceptable. Application is generally further constrained by the social conditions, level of infrastructure and other conditions typical of many Article 5 countries.

At present there is no single in-kind alternative for all uses of methyl bromide in developing countries. For some quarantine applications (e.g. certain berryfruit infested with thrips or aphids, certain unwashed root vegetables infested with soil pests) there are currently no technically feasible alternatives.

It may be possible to use alternative treatments and/or production methods, including IPM strategies, to substitute for most of the pest control uses of methyl bromide. However, the varied and special conditions in Article 5 countries require that the alternatives be appropriately adapted to the climatic conditions, particular cropping techniques, resource availability and specific target pests. Different alternatives will have to be used for different crops, commodities and situations. This is likely to involve significant effort to select appropriate alternatives, adaptive research, field testing, technology transfer, user education, institutional capacity building and training, among other factors. It is critical that those Article 5 countries which utilize methyl bromide receive technical and financial assistance to introduce or adapt alternative materials and methods to manage the pests currently controlled by methyl bromide.

The Committee noted that the specified incremental costs eligible for funding under the Multilateral Fund and items on the indicative list may need revision in order to accommodate the special needs associated with methyl bromide, if phaseout is considered.

Potential trade restrictions relating to methyl bromide use are of great concern to those Article 5 countries dependent on certain exports now produced with the aid of methyl bromide. Such restrictions, which could be applied by developed, importing countries and regions, as a result of their own or international restrictions on methyl bromide, are seen as an issue of substantial importance. They could nullify the effect of any grace period.

Montreal Protocol on Substances that Deplete the Ozone Layer

UNEP 1994 Report of the Methyl Bromide Technical Options Committee

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Contents

Page No.

Executive Summary ... 1

1. Committee mandate ... 1

2. Existing uses of methyl bromide ... 1

3. Emissions from methyl bromide use, and their reduction, including recovery ... 2

4. Alternatives to methyl bromide ... 3

4.1 Alternatives on a sector basis ... 4

4.1.1 Soils ... 4

4.1.2 Durables ... 5

4.1.3 Perishables ... 5

4.1.4 Structures and transportation vehicles ... 6

5. Concerns relating to Article 5 countries ... 7

Contents ... 8

Methyl Bromide Technical Options Committee - composition and organisation at 1 December 1994 ... 24

Glossary ... 27

1.0 INTRODUCTION ... 28

1.1 References ... 30

Annex 1.1 - Decisions taken by the Parties at the fourth (Copenhagen) meeting relevant to methyl bromide and MBTOC ... 31

2.0 CURRENT APPLICATIONS OF METHYL BROMIDE ... 35

2.1 General scope of use ... 35

2.2 Supply of methyl bromide ... 37

2.3 Application methods 37

  2.3.1 Soil fumigation 37

    2.3.1.1 Manual application 37

    2.3.1.2 Mechanised injection 38

  2.3.2 Application to commodities and structures 38

2.4 Global quantities of methyl bromide used 39

2.5 Technical and legislative limitations to methyl bromide use 43

  2.5.1 Technical limitations 43

  2.5.2 Legislative limitations 43

2.6 References 44

3.0 EMISSIONS, EMISSION REDUCTION AND RECLAMATION, RECOVERY AND RECYCLING OF METHYL BROMIDE 45

Executive Summary 45

3.1 Definitions 46

3.2 Emissions of methyl bromide from treatments 46

3.3 Global warming potential and alternatives 49

3.4 Opportunities for methyl bromide emission 50

3.5 Containment 51

  3.5.1 Soil fumigation 51

  3.5.2 Structural and commodity fumigation 52

3.6 Recovery 53

  3.6.1 Activated carbon 53

  3.6.2 Condensation/activated carbon 54

  3.6.3 Absorption into reactive liquids 54

  3.6.4 Adsorption onto zeolite 55

  3.6.5 Techniques under development 55

3.7 Reclamation and Recycling 56

  3.7.1 Condensation/activated carbon 56

  3.7.2 Activated carbon 56

3.7.3 Zeolite 57

3.8 Constraints 57

3.9 References 57

Annex 3.1 - Calculation of % emission of methyl bromide from treatments using the mass balance approach 60

1. Derivation of formula 60

2. Calculation of emission of methyl bromide from bulk and bag stack treatments of grain 60

3. Calculation of methyl bromide emissions from treatment of dried fruits and nuts 61

3.1 Dried fruits 61
3.2 Nuts 62

4. Calculation of methyl bromide emissions from treatment of perishables 62

4.1 Nectarines 62

5. Sample calculations for emissions of methyl bromide resulting from fumigation of timber (logs) in the hold of a ship prior to import into Japan (data source: A. Tateya, MAFF, Japan) 62

4.0 ALTERNATIVES TO METHYL BROMIDE 64

4.1 Alternatives for soil treatment 64

Executive Summary 64

4.1.1 Introduction 67

4.1.2 Existing uses of methyl bromide 68

4.1.2.1 Application of methyl bromide 68

4.1.3 Training and worker protection 69

4.1.4 Soil pest management strategies 69

4.1.4.1 Monitoring and pest detection 70

4.1.5 Soil pest management alternatives to methyl bromide 70

4.1.5.1 Non-chemical methods 70

4.1.5.1.1 Organic amendments 70
4.1.5.1.2 Biological control 71
4.1.5.1.3 Cultural practices 73
4.1.5.1.4 Plant breeding and grafting 75
4.1.5.1.5 Physical methods 76

4.1.5.1.6 Research priorities for non-chemical alternatives 78

4.1.5.2 Chemical methods 79

4.1.5.2.1 Fumigants 79
4.1.5.2.2 Non-fumigants 81
4.1.5.2.3 Chemical alternatives which require further development 81
4.1.5.2.4 Research priorities for chemical alternatives 83

4.1.6 Emission reduction 83

4.1.6.1 Reduced dosage 83
4.1.6.2 Plastic soil covers 84
4.1.6.3 Improving application techniques 84
4.1.6.4 Reducing leakage during greenhouse fumigation 84
4.1.6.5 Use of diffusion enhancing co-fumigants 85
4.1.6.6 Reduced frequency of application 85
4.1.6.7 Research priorities for reduced emissions 85

4.1.7 Research priorities 85

4.1.8 Transfer of knowledge and training in improvements 86

4.1.9 Uses without known alternatives 86

4.1.10 Constraints 87

4.1.10.1 Environmental 87
4.1.10.2 Logistical 87
4.1.10.3 Health, safety and environment 88
4.1.10.4 Biotic 88
4.1.10.5 Informational 88
4.1.10.6 Economic 89
4.1.10.7 Sociological/psychological 89

4.1.11 General conclusions 89

4.1.12 References 90

Case history 4.1.1: Methyl bromide reduction and elimination in horticultural production in Italy 99

Case history 4.1.2: Forest tree nurseries in the People's Republic of China .. 102

Case history 4.1.3: Alternatives in forest tree nurseries in the USA (Pacific Northwest) and Western Canada 104

Case history 4.1.4: Use of alternatives in vineyards in California, USA 106

Case history 4.1.5: Replacement of methyl bromide use in horticultural nurseries, Ohio 108

Case history 4.1.6: Organic strawberries in California 109

Annex 4.1.1 - Methyl bromide soil fumigation use survey 111

Annex 4.1.2 - Soilborne pathogens, nematodes, arthropods, and weeds controlled by soil fumigation with methyl bromide in various countries or regions of the world 120

Annex 4.1.3 - Sample toxicological data for chemical alternatives to methyl bromide for soil treatment 122

Annex 4.1.4 - Discussion on potential use rate reductions on methyl bromide conducted at MBTOC Bordeaux meeting and through subsequent communications among members of the Soil fumigation subcommittee 124

4.2 Alternatives for treatment of durables 132

Executive summary 132

4.2.1 Introduction 133

4.2.2 Existing uses of methyl bromide 134

- 4.2.2.1 Target pests 135
- 4.2.2.2 Types of fumigation enclosure 136

4.2.3 General description of alternatives 136

- 4.2.3.1 Fumigants and other gases 136
  - 4.2.3.1.1 Phosphine 136
  - 4.2.3.1.2 Hydrogen cyanide 137
  - 4.2.3.1.3 Ethyl formate 138
  - 4.2.3.1.4 Carbon bisulphide 138
  - 4.2.3.1.5 Carbonyl sulphide 138
  - 4.2.3.1.6 Ozone 138
  - 4.2.3.1.7 Methyl isothiocyanate (MITC) 138
  - 4.2.3.1.8 Sulphuryl fluoride 138
  - 4.2.3.1.9 Ethylene oxide 139
  - 4.2.3.1.10 Controlled and modified atmospheres 139
- 4.2.3.2 Contact insecticides 140
  - 4.2.3.2.1 Organophosphorus compounds 141
  - 4.2.3.2.2 Synthetic pyrethroids 141
  - 4.2.3.2.3 Botanicals 142
  - 4.2.3.2.4 Insect growth regulators (IGRs) 142
  - 4.2.3.2.5 Inert dusts 142
- 4.2.3.3 Physical control methods 143
  - 4.2.3.3.1 Cold treatments 143
  - 4.2.3.3.2 Heat treatment 144
  - 4.2.3.3.3 Irradiation 144
  - 4.2.3.3.4 Physical removal (sanitation) 145
- 4.2.3.4 Biological methods 145
  - 4.2.3.4.1 Biological control with predaceous insects or parasitoids 145

4.2.3.4.2 Insect pathogens as microbial control agents 146
4.2.3.4.3 Pheromones 146

4.2.4 Alternatives to methyl bromide in stored cereal grains and similar commodities 147

4.2.4.1 Commodities and pests 147

4.2.4.2 Scope of the problem 148

4.2.4.3 Existing substitutes for cereal grain and similar commodities 149

4.2.4.3.1 Phosphine 149
4.2.4.3.2 Controlled atmospheres (CA) 150
4.2.4.3.3 Grain protectants 150
4.2.4.3.4 Physical control methods 151

4.2.4.3.4.1 Gamma ray or accelerated electron irradiation 151
4.2.4.3.4.2 Heat treatment 151
4.2.4.3.4.3 Cold treatments 152

4.2.4.3.5 Biological control methods 152

4.2.4.3.5.1 Biological control with predaceous insects or parasites 152
4.2.4.3.5.2 Insect pathogens of microbial origin 152
4.2.4.3.5.3 Pheromones 152

4.2.5 Substitutes in dried fruit and nuts 153

4.2.5.1 Definition of commodities and pests 153

4.2.5.2 Scope of the problem 156

4.2.5.3 Existing substitutes 157

4.2.5.3.1 Phosphine 157

4.2.5.4 Other fumigants and gases 157

4.2.5.4.1 Hydrogen cyanide 157
4.2.5.4.2 Ethyl formate 158

4.2.5.5 Controlled atmospheres 158

4.2.5.6 Contact insecticides and inert dusts 158

4.2.5.7 Physical methods 159

4.2.5.7.1 Irradiation 159
4.2.5.7.2 Optimised hot and cold treatments 159

4.2.5.8 Biological methods 159

4.2.5.9 Others 160

4.2.5.9.1 Packaging and containerisation 160
4.2.5.9.2 Detection, sorting, certification 160
4.2.5.9.3 Engineering 160
4.2.5.9.4 Genetic engineering 160
4.2.5.9.5 Combination of processes - IPM systems .. 160

4.2.6 Beverage crops 161

4.2.6.1 Definition of commodities and pests 161

4.2.6.2 Scope of the problem 161

4.2.6.3 Existing substitutes 162

4.2.6.3.1 Phosphine 162

4.2.6.4 Other fumigants and gases 162

4.2.6.4.1 Hydrogen cyanide 162
4.2.6.4.2 Controlled and modified atmospheres 162

4.2.6.5 Contact insecticides 162

4.2.6.6 Physical methods 162

4.2.6.6.1 Irradiation 162
4.2.6.6.2 Temperature control 163

4.2.7 Herbs and spices 163

4.2.7.1 Definition of commodities and pests 163

4.2.7.2 Scope of the problem 164

4.2.7.3 Existing substitutes 164

4.2.7.3.1 Phosphine 164

4.2.7.4 Other fumigants and gases 164

4.2.7.4.1 Ethylene oxide 164
4.2.7.4.2 Controlled and modified atmospheres 165

4.2.7.5 Contact insecticides 165

4.2.7.6 Physical control methods 165

4.2.7.6.1 Irradiation 165
4.2.7.6.2 Heat and cold treatments 165

4.2.8 Tobacco 165

4.2.8.1 Definition of commodities and pests 165

4.2.8.2 Scope of the problem 166

4.2.8.3 Existing substitutes 166
4.2.8.3.1 Phosphine 166

4.2.8.4 Contact insecticides 166

4.2.8.5 Physical control methods 166

4.2.8.5.1 Irradiation 166
4.2.8.5.2 Heat and cold treatment 167

4.2.9 Artefacts 167

4.2.9.1 Definition of commodities and pests 167

4.2.9.2 Scope of the problem 168

4.2.9.3 Existing substitutes 168

4.2.9.3.1 Phosphine 168

4.2.9.4 Other fumigants and gases 168

4.2.9.4.1 Controlled/modified atmospheres 168

4.2.9.5 Contact insecticides 168

4.2.9.6 Physical methods 168

4.2.9.6.1 Irradiation 168
4.2.9.6.2 Heat and cold treatment 169

4.2.10 Logs, timber, bark and wood products 169

4.2.10.1 Insect control 169

4.2.10.1.1 Definition of commodities and pests 169
4.2.10.1.2 Scope of the problem 170
4.2.10.1.3 Existing substitutes 170

4.2.10.1.3.1 Phosphine 171
4.2.10.1.3.2 Sulphuryl fluoride 171
4.2.10.1.3.3 Contact insecticides 171

4.2.10.1.4 Physical control methods 171

4.2.10.1.4.1 Irradiation 171
4.2.10.1.4.2 Other methods 171

4.2.10.2 Control of fungi 172

4.2.10.2.1 Target pests 172
4.2.10.2.2 Contact fungicides ('Wood preservatives') 172

4.2.10.2.2.1 Bifluorides 172

4.2.10.2.3 Physical control methods 172

4.2.10.2.3.1 Heat treatment 172

4.2.11 Seeds for planting 172

4.2.11.1 Scope of the problem 172

4.2.11.2 Existing substitutes 174

4.2.11.2.1 Phosphine 174

4.2.11.3 Chemical soaking and fumigation 174

4.2.11.4 Physical control methods 174

4.2.11.4.1 Cleaning 174
4.2.11.4.2 Hot water treatment 174

4.2.12 Dried fish, meat and seafood 174

4.2.12.1 Definition of commodities and pests 174

4.2.12.2 Scope of the problem 175

4.2.12.3 Existing substitutes 175

4.2.12.3.1 Phosphine 175

4.2.12.4 Contact insecticides 175

4.2.12.5 Physcial control methods 175

4.2.12.5.1 Irradiation 175

4.2.13 Reducing emissions 176

4.2.14 Transfer of knowledge and training in improvements and alternatives 177

4.2.15 Research priorities 177

4.2.16 Uses without known alternatives 179

4.2.17 Constraints 179

4.2.17.1 Consumer acceptance and registration of chemicals 179
4.2.17.2 Technical aspects 179
4.2.17.3 Quarantine 180

4.2.18 References 180

Case history 4.2.1: Rice irradiation in Indonesia 194

Annex 4.2.1 - Minimum exposure periods (days) required for control of all stages of the stored product pests listed, based on a phosphine concentration of 1.0 g m^{-3} 196

Annex 4.2.2 - Sample toxicological data on pesticides used for treating durable commodities and structures 197

Annex 4.2.3 - Estimates of the minimum *ct*-product (g h m^{-3}) of methyl bromide for a 99.9 per cent kill of various stages of a number of insect species at 10, 15, 25 and 30°C and 70 per cent RH. (Heseltine and Thompson, 1974) 201

Annex 4.2.4 - Methyl bromide dosage table. European Plant Protection Organization (1993) 202

4.3 Alternatives for treatment of perishables 203

Executive summary 203

4.3.1 Introduction 206

4.3.2 Existing uses of methyl bromide 207

4.3.3 Characteristics of potential alternatives 208

- 4.3.3.1 Preharvest practices and inspection procedures 208
  - 4.3.3.1.1 Cultural practices leading to pest reduction 208
  - 4.3.3.1.2 Pest-free zones and periods 209
  - 4.3.3.1.3 Inspection and certification 209
- 4.3.3.2 Postharvest treatments 210
  - 4.3.3.2.1 Non-chemical alternatives 210
    - 4.3.3.2.1.1 Cold treatment 210
    - 4.3.3.2.1.2 Heat treatment 210
    - 4.3.3.2.1.3 Controlled atmosphere ... 211
    - 4.3.3.2.1.4 Modified atmosphere 211
    - 4.3.3.2.1.5 Irradiation 212
    - 4.3.3.2.1.6 Microwaves 212
    - 4.3.3.2.1.7 Physical removal 212
    - 4.3.3.2.1.8 Combination treatments .. 212
  - 4.3.3.2.2 Chemical alternatives 213
    - 4.3.3.2.2.1 Fumigation 213
    - 4.3.3.2.2.2 Chemical dips 213
  - 4.3.3.2.3 Constraints to acceptance of alternatives 213

4.3.4 Suitability of alternatives for controlling pests on each group of commodities 214

- 4.3.4.1 Apples and pears 214
- 4.3.4.2 Stonefruit 215
- 4.3.4.3 Citrus 216
- 4.3.4.4 Grapes 217

4.3.4.5 Berryfruit 217
4.3.4.6 Root crops 218
4.3.4.7 Vegetables 218
4.3.4.8 Cucurbits 219
4.3.4.9 Tropical fruit 220
4.3.4.10 Cut flowers and ornamentals 221
4.3.4.11 Bulbs 222

4.3.5 Summary table of existing and potential alternatives to methyl bromide for disinfestation 222

4.3.5.1 Cultural Practices (Systems Approach, Multiple Pest Decrement 222
4.3.5.2 Pest-free Zones and Periods 223
4.3.5.3 Inspection and Certification 223
4.3.5.4 Cold Treatment 223
4.3.5.5 Heat Treatments 224
4.3.5.6 Controlled Atmospheres 224
4.3.5.7 Modified Atmospheres 224
4.3.5.8 Irradiation 225
4.3.5.9 Microwaves 225
4.3.5.10 Physical Removal of Pests 225
4.3.5.11 Combined Treatments 225
4.3.5.12 Fumigation 226
4.3.5.13 Chemical Dips 226

4.3.6 Commodities without approved quarantine alternatives to methyl bromide 226

4.3.7 Opportunities to reduce emissions 227

4.3.8 Research priorities 227

4.3.8.1 Developing countries 227
4.3.8.2 Developed countries 228

4.3.9 Transfer of knowledge, and training in improvements and alternatives 228

4.3.10 Developing country issues 228

4.3.11 References 229

Case history 4.3.1: Heat disinfestation treatments for payaya in Hawaii 236

Annex 4.3.1 - List of countries that were sent forms to determine the postharvest use of methyl bromide on perishable commodities 238

Annex 4.3.2 - Forms sent to government organisations within each country to determine the postharvest use of methyl bromide on perishable commodities 239

Annex 4.3.3 - Perishable commodities treated with methyl bromide, at least on some occasions, for disinfestation and pest control 247

Annex 4.3.4 - Examples of fumigation of imports as a condition of entry 253

Annex 4.3.5 - Examples of fumigation of exports as a condition of entry 256

Annex 4.3.6 - Examples of fumigation for shipment within the same country 259

4.4 Alternatives for treatment of structures and transportation 260

Executive Summary 260

4.4.1 Introduction 261

4.4.2 Existing uses of methyl bromide in structural fumigation 264

- 4.4.2.1 Pests other than wood destroying insects 264
- 4.4.2.2 Wood destroying insects 265
- 4.4.2.3 Transport vehicles 265

4.4.3 Substitutes and alternatives to methyl bromide 266

- 4.4.3.1 Substitutes and alterantives for pests other than wood destroying insects 266
  - 4.4.3.1.1 Fumigants 268
  - 4.4.3.1.2 Controlled atmospheres 269
  - 4.4.3.1.3 Combinations 269
  - 4.4.3.1.4 Nonfumigant pesticides 269
  - 4.4.3.1.5 Nonchemical treatments 270
- 4.4.3.2 Substitutes and alternatives for wood destroying insects 271
  - 4.4.3.2.1 Fumigants 272
  - 4.4.3.2.2 Nonfumigant pesticides 273
  - 4.4.3.2.3 Nonchemical 274
- 4.4.3.3 Ships, aircraft and other transport vehicles 274
  - 4.4.3.3.1 Ships 274
  - 4.4.3.3.2 Aircraft 275
  - 4.4.3.3.3 Other vehicles (freight trucks, railcars, etc.) 275

4.4.4 Containment/methods for reducing current methyl bromide use 275

- 4.4.4.1 Improved containment 275
- 4.4.4.2 Methyl bromide and carbon dioxide 276
- 4.4.4.3 Volume displacement technologies 276

4.4.5 Transfer of knowledge and training 276

4.4.6 Research requirements 276

- 4.4.6.1 Emission reduction for methyl bromide 276
- 4.4.6.2 Substitutes and alternatives 277

4.4.7 Uses without alternatives 277

4.4.8 Feasible reduction in methyl bromide use 277

4.4.9 Constraints 278

4.4.10 Developing country issues 278

4.4.11 References 280

Case history 4.4.1: Heat treatment of flour mill and cleaning house 281

Case history 4.4.2: Moth control in flour mills using mass trapping, mating disruption and attracticide method 282

Case history 4.4.3: Fumigation of three stave churches in Norway, August - September 1984 283

5.0 DEVELOPING COUNTRY ISSUES 284

Executive Summary 284

5.1 Introduction 284

5.2 Methyl bromide use in Article 5 countries 285

5.3 Soil fumigation 289

5.3.1 Progress on development and adoption of alternatives to methyl bromide use in soil fumigation 290

5.4 Fumigation of durables 290

5.4.1 Progress on development and adoption of alternatives to methyl bromide in durable commodity pest control 291

5.5 Fumigation of perishables 291

5.5.1 Progress on development and adoption of alternatives to methyl bromide in perishable fumigation 292

5.6 Structural fumigation 292

5.6.1 Progress on development and adoption of alternatives to methyl bromide for structural fumigation 292

5.7 Recycling, recovery and reclamation 293

5.8 Replacement of methyl bromide 293

5.9 Conclusion 293

Appendix: UNEP Methyl Bromide Technical Options Committee address list as at 1 December 1994 295

LIST OF TABLES

Page No.

2.1 Global sales of methyl bromide (tonnes) by use sector (China, India and former USSR not included) 36

2.2 Sales of methyl bromide by region, including chemical feedstock, but excluding China, India and former USSR 41

2.3 Global methyl bromide usage (tonnes, 1992) by sector 42

3.1 Estimated usage of methyl bromide and emissions to atmosphere for different categories of fumigation 48

3.2 Half-life and % methyl bromide remaining in soil (laboratory studies) after 3 and 7 days. Calculated from data reviewed in Visser and Linders (1992) 49

3.3 Relative global warming calculations for methyl bromide and steam sterilisation as an alternative soil treatment 50

3.4 Emissions from a methyl bromide fumigation of greenhouse soil using two different covers (from de Heer *et al.* 1981) 51

3.5 Examples of pressure test standards for gastightness of some fumigation enclosures and treated structures 52

3.6 Fumigation of cereal grains on import into Japan (1992 data) with calculated emissions of methyl bromide based on bromide ion residue levels in commodity after treatment. Data source: A. Tateya, MAFF, Japan 61

4.1.1 Production yields and costs for forest tree nurseries in the PRC 103

4.1.2 Comparison of conventional and organic strawberry production in California, USA 110

4.1.3 Responses to MBTOC survey on methyl bromide use as soil fumigant 112

4.1.4 MBTOC survey results. Methyl bromide use as soil fumigant by country and use sector 113

4.1.5 Dosage reduction in 10 years (by 2004) 125

4.1.6 Feasible reductions in methyl bromide soil fumigant use 127

4.1.7 Dosage reduction in 10 years 131

4.2.1 The basic differences between contact insecticides and fumigants 141

4.2.2 Examples of cereal and legume crops which may be fumigated with methyl bromide 147

4.2.3 Principal pests of cereals and similar commodities 148

4.2.4 Varieties of nuts and fruits sometimes treated with methyl bromide 153

4.2.5 Target pests of dried fruits and nuts 155

4.2.6 World production of main dried fruits and nut crops. 3 year average (1990/91 - 1992/93) 156

4.2.7 Target pests in beverage crops 161

4.2.8 Herbs and spices sometimes disinfested with methyl bromide 163

4.2.9 Some target pests in herbs and spices 164

4.2.10 Target pests in tobacco and related products 166

4.2.11 Some common pests of artefacts made of wood, skin, feathers, wool and other organic materials 167

4.2.12 Target insect pests in logs, timber and bark products 170

4.2.13 Some nematodes transmitted by seeds 173

4.2.14 Common pests in dried fish, meat and seafood 175

4.2.15 Minimum exposure periods (days) required for control of all stages of the stored product pests listed, based on a phosphine concentration of 1.0 g m^{-3}. This dosage is as recommended for good conditions and the dosage applied will usually need to be increased considerably in leaky situations (EPPO, 1984) 196

4.2.16 Estimates of the minimum *ct*-product (g h m^{-3}) of methyl bromide for a 99.9 per cent kill of various stages of a number of insect species at 10, 15, 25 and 30°C and 70 per cent RH. (Heseltine and Thompson, 1974) 201

4.2.17 Methyl bromide dosage table. European Plant Protection Organization (1993) 202

4.3.1 List of countries that were sent forms to determine the postharvest use of methyl bromide on perishable commodities 238

4.3.2 Examples of fumigation of imports as a condition of entry 253

4.3.3 Examples of fumigation of exports as a condition of entry 256

4.3.4 Examples of fumigation for shipment within the same country 259

4.4.1 Methyl bromide usage for structural pest control. Global estimate for 1992 263

4.4.2 Estimates for feasible reductions in structural uses of methyl bromide by 1998 and 2003 279

5.1 Consumption of methyl bromide by some Article 5 countries (1992) 286

5.2 Consumption of methyl bromide (t) in developing countries in three regions (1992) 288

LIST OF FIGURES

2.1 Total global sales of methyl bromide (excluding China, India and former USSR) on an annual basis for the period 1984 to 1992 excluding feedstock uses.......40

4.1.1 Global methyl bromide use for soil fumigation - by country. 1992. MBTOC survey data.......117

4.1.2 Global use of methyl bromide (excluding USA) for soil fumigation - by use category. 1992. MBTOC survey data.......117

4.1.3 Use of methyl bromide in USA in 1992 for soil fumigation - by use category. MBTOC survey data.......118

4.1.4 Global use of methyl bromide for soil fumigation - by major crop. Minor uses not included. 1992. MBTOC survey data.......118

4.1.5 Global use of methyl bromide for soil fumigation (excluding USA) - for major crops only. 1992. MBTOC survey data.......119

4.1.6 Use of methyl bromide for soil fumigation in USA - major crops only. 1992. MBTOC survey data.......119

Methyl Bromide Technical Options Committee - composition and organisation at 1 December 1994

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Rodrigo Rodriguez-Kabana	Auburn University	USA
Subcommittee chairs and co-chairs		
Chair - 'Reclamation, Recovery and Recycling'		
Don Smith	Industrial Research Limited	New Zealand
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Frank Westerlund	California Strawberry Commission	USA

Glossary

The following abbreviations and acronyms are used commonly throughout this report:

1,3-D	1,3-dichloropropene
Bt	*Bacillus thuringiensis*, a microorganism which produces insecticidal toxins
CA	Controlled atmospheres. Storage of pest control atmospheres with a set combination of the atmospheric gases, oxygen, nitrogen and carbon dioxide (CO_2). Strictly, a controlled atmosphere is one where the composition, typically low in oxygen, is regulated by some means (see also MA), such as by adding gas continuously or from time to time to the system.
CO_2	Carbon dioxide
ct-product	The value obtained by multiplying the concentration of a fumigant (*c*) by the time of exposure (*t*). Under varying concentrations the *ct*-product is given by the integral of *c* over time. Used as a measure of exposure of pests to fumigants.
EDB	Ethylene dibromide
EPPO	European Plant Protection Organisation
HCN	Hydrogen cyanide
IPM	Integrated Pest Management systems. A rational combination of measures designed to provide optimum control of pests. Usually associated with use of non-chemical as well as chemical measures.
MA	Modified Atmospheres. Storage or pest control atmospheres in which the normal content of oxygen, nitrogen and CO_2 is changed by natural processes such as respiration, sometimes with an initial purge with gases such as nitrogen or CO_2, but not controlled within set limits by further addition of gas.
MBTOC	Methyl Bromide Technical Options Committee.
MeBr	Methyl Bromide
MITC	Methyl isothiocyanate
NGO	Nongovernmental Organisation
TEAP	Technology and Economics Assessment Panel.

1.0 INTRODUCTION

Methyl bromide was listed as an ozone-depleting substance by the Fourth Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer in Copenhagen in November 1992. At that time no date for phase out of methyl bromide use (production/consumption) was set although the annual consumption by signatories to the Protocol was limited to 1991 levels by 1995. Exemptions were made for Article 5 countries and for methyl bromide used in preshipment and quarantine treatments. Details of the Decisions relevant to methyl bromide made by the Parties at the Copenhagen meeting are given in Annex 1.1.

There are several sources of atmospheric methyl bromide. Some of these result from release of manufactured methyl bromide into the atmosphere, some result inadvertently from the activities of humans, while others originate entirely from natural sources. Estimates of the relative contribution of the different sources is given in the 1994 Report of the Science Panel. The main anthropogenic, and thus controllable, contribution to the atmospheric methyl bromide load results from use of manufactured gas as a fumigant.

This report is produced in response to Decision IV/23 of the Copenhagen meeting, which called, inter alia, for a technical assessment of the alternatives to *current uses* of methyl bromide, their economic feasibility, their suitability for developing countries and their potential for global warming.

There are two main uses of methyl bromide which fall under this Decision: as a fumigant and as a chemical feedstock. The use of methyl bromide as a fire extinguisher is now discontinued.

This report is restricted to a detailed technical assessment of methyl bromide as a fumigant. Economic feasibility of the alternatives has been considered by the Economics Options Committee of the Technology and Economics Assessment Panel. Use of methyl bromide as a chemical feedstock is exempted from control under the Montreal Protocol as it is used as an intermediate in chemical synthesis in fully contained systems and results in only minor and inadvertent emissions.

Methyl bromide is widely used as a fumigant in agriculture and pest control in structures, stored commodities and quarantine treatments. It is active against a diverse variety of organisms at low concentration, including mammals and many insects, mites, nematodes, fungi, weeds, bacteria and viruses. The broad spectrum of activity and ease of application of the material have led to its use as the treatment of choice in a number of situations. Several agricultural production systems involving intensive production of high value crops have become dependent on use of methyl bromide. Production of high value export crops in some Article 5 countries, notably tobacco, some cut flowers, and some vegetables and fruit may also use methyl bromide for pest, weed and pathogen control.

In this report a general summary of the use of methyl bromide fumigant is given. This is followed, first by discussion of recapture/recycling and emission reduction technology, then by discussion of specific alternatives and practices under four categories, corresponding to the main areas of application of methyl bromide. These are:

- as a soil fumigant
- as a fumigant for durable commodities
- as a fumigant for perishable commodities
- as a fumigant for structures in a broad sense, including buildings and transport vehicles and containers.

Finally, concerns of Article 5 countries are discussed in relation to use of methyl bromide, barriers to adoption of alternatives, and implications of possible phaseout of the material.

An important use of methyl bromide, for both developing and developed countries, is for preshipment and quarantine treatments. Methyl bromide may be particularly difficult to replace in such situations despite the availability of apparently technically feasible alternatives, as its use may be specified by bilateral agreement. Establishment of alternatives may require extensive demonstration trials and negotiation.

Almost all treatments of perishable commodities, typically fruit and vegetables come under the categories of preshipment and quarantine treatment as defined. They are for the purposes of control of pests which do not normally multiply on the commodity after harvest. In contrast much of the use of methyl bromide on durables, notably in Article 5 countries, is to control pests that can complete their life cycle on the commodity in storage. Treatments are often to prevent damage to the commodity, not primarily to restrict the spread of pests.

Case histories showing application of particular alternative technologies are given where there are no adequate published references. These provide evidence that particular proposed alternatives work in practice. The Committee assumed that a technology demonstrated or in use in one region of the world would be applicable in another unless there were obvious technical constraints to the contrary (eg. very different climate). However, it was noted that frequently there will be non-technical barriers to the adoption of a technically feasible alternative. In many cases, the principal impediment to rapid adoption of an alternative will be regulatory, as the alternative may need approval for use under regulation relating to substances involved in pest control or contact or exposure to foodstuffs.

Surveys on methyl bromide use were conducted by MBTOC in an attempt to determine the particular uses of the fumigant and what was the consumption of methyl bromide in particular applications. These surveys were conducted through questionnaires sent to ministries concerned with agriculture and the environment in various Parties to the Protocol. Results are given in this Report.

This Report follows on from the preliminary UNEP assessment report on methyl bromide (UNEP, 1992). There have been several meetings apart from those of MBTOC held to discuss methyl bromide and alternatives. Proceedings and other publications are available from some of these (Anon., 1992, 1993; Civerolo *et al.*, 1993; Hallas, *et al.*, 1994) which provide further information on particular aspects of alternative technologies and the current role of methyl bromide.

A workshop was recently held in Orlando, Florida (November, 1994) to discuss methyl bromide and alternatives. The toxicology of methyl bromide has been recently reviewed in depth (Anon., in press). There have also been a number of economic studies which have included discussion of some technical aspects of methyl bromide use and alternatives. These are under review by the Economics Option Committee of TEAP.

The Committee process which generated this Report brought together experts, government nominees, industry, NGOs and other interested individuals from a broad range of disciplines and backgrounds. At 1 November 1994, MBTOC had 68 members from 23 countries, including 8 Article 5 countries. In the course of creating and debating this report, MBTOC met five times (April 1993, The Hague, The Netherlands; July 1993, Nairobi/Harare, Kenya/Zimbabwe; October 1993, Washington, United States of America; March 1994, Santiago, Chile; and August 1994, Bordeaux, France). This international group considered the practice of fumigation across all applications, rather than concentrating on particular subdisciplines, such as soil fumigation or disinfestation of perishables. This has highlighted several technical deficiencies, given in the body of the report and, in particular, drawn attention to the lack of effective information transfer on fumigation technology and alternatives thereto.

One outcome of the work of the Committee has been to emphasise the large range of alternatives available for many situations in which methyl bromide is currently used.

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Annex 1.1

Decisions taken by the Parties at the fourth (Copenhagen) meeting relevant to methyl bromide and MBTOC

Annex XV

RESOLUTION ADOPTED BY THE PARTIES TO THE MONTREAL PROTOCOL ON SUBSTANCES THAT DEPLETE THE OZONE LAYER

Methyl bromide

The Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer

Resolve in the light of serious environmental concerns raised in the scientific assessment, to make every effort to reduce emissions of and to recover, recycle and reclaim, methyl bromide. They look forward to receiving the full evaluations to be carried out by the UNEP Scientific Assessment Panel and the Technology and Economic Assessment Panel, with a view to deciding on the basis of these evaluations no later than at their Seventh Meeting, in 1995, a general control scheme for methyl bromide, as appropriate, including concrete targets beginning, for Parties not operating under paragraph 1 of Article 5, with, for example a 25 per cent reduction as a first step, at the latest by the year 2000, and a possible phase-out date.

I. *Article 2H: Methyl Bromide*

The following Article shall be inserted after Article 2G of the Protocol:

Article 2H: Methyl Bromide

Each Party shall ensure that for the twelve-month period commencing on 1 January 1995, and in each twelve-month period thereafter, its calculated level of consumption of the controlled substance in Annex E does not exceed, annually, its calculated level of consumption in 1991. Each Party producing the substance shall, for the same periods, ensure that its calculated level of production of the substance does not exceed, annually, its calculated level of production in 1991. However, in order to satisfy the basic domestic needs of the Parties operating under paragraph 1 of Article 5, its calculated level of production may exceed that limit by up to ten per cent of its calculated level of production in 1991. The calculated levels of consumption and production under this Article shall not include the amounts used by the Party for quarantine and pre-shipment applications.

Decision IV/13. Assessment panels

1. To note with appreciation the work done by the Panels for Ozone Scientific Assessment, Environmental Effects Assessment, and Technology and Economic Assessment in their reports of November-December 1991;

2. To request the Technology and Economic Assessment Panel and its Technical and Economic Options Committees to report annually to the Open-ended Working Group of the Parties to the Montreal Protocol the technical progress in reducing the use and emissions of controlled substances and assess the use of alternatives, particularly their direct and indirect global-warming effects;

3. To request the three assessment panels to update their reports and submit them to the Secretariat by 30 November 1994 for consideration by the Open-ended Working Group and by the Seventh Meeting of the Parties to the Montreal Protocol. These assessments should cover all major facets discussed in the 1991 assessments with enhanced emphasis on methyl bromide. The scientific assessment should also include an evaluation of the impact of sub-sonic aircraft on ozone;

4. To encourage the panels to meet once a year to enable the co-chairpersons of the panels to bring to the notice of the meetings of the Parties to the Montreal Protocol, through the Secretariat, any significant developments which, in their opinion, deserve such notice;

Decision IV/23. Methyl bromide

1. To request the Scientific Assessment Panel and the Technology and Economic Assessment Panel to assess the following, in accordance with Article 6 of the Protocol, and to submit their combined report, through the Secretariat, by 30 November 1994 at the latest, to the Seventh Meeting of the Parties:

   (a) Abundance of methyl bromide in the atmosphere and the proportion of anthropogenic emissions within this abundance of methyl bromide and the ozone-depleting potential of methyl bromide;

   (b) Methodologies to control emissions into the atmosphere from the various current uses of methyl bromide and the technical and economic feasibility and the likely results of such controls;

   (c) Availability of chemical and non-chemical substitutes for the various current uses of methyl bromide; their cost-effectiveness; the incremental costs of such substitutes, technological and economic feasibility of substitution for various uses and the benefits to the protection of the ozone layer by such substitution, taking into account the particular social, economic, geographic and agricultural conditions of different regions and, specifically, the developing countries;

2. To request the Open-ended Working Group of the Parties to the Montreal Protocol to consider this report and submit its recommendations to the Seventh Meeting of the Parties in 1995;

Decision IV/24. Recovery, reclamation and recycling of controlled substances

1. To annul decision I/12 H of the First Meeting of the Parties, which reads "Imports and exports of bulk used controlled substances should be treated and recorded in the same manner as virgin controlled substances and included in the calculation of the Party's consumption limits";

2. Not to take into account, for calculating consumption, the import and export of recycled and used controlled substances (except when calculating the base year consumption under paragraph 1 of Article 5 of the Protocol), provided that data on such imports and exports are subject to reporting under Article 7;

3. To agree to the following clarifications of the terms "recovery", "recycling" and "reclamation":

(a) *Recovery*: The collection and storage of controlled substances from machinery, equipment, containment vessels, etc., during servicing or prior to disposal;

(b) *Recycling*: The re-use of a recovered controlled substance following a basic cleaning process such as filtering and drying. For refrigerants, recycling normally involves recharge back into equipment it often occurs "on-site";

(c) *Reclamation*: The re-processing and upgrading of a recovered controlled substance through such mechanisms as filtering, drying, distillation and chemical treatment in order to restore the substance to a specified standard of performance. It often involves processing "off-site" at a central facility;

4. To urge all the Parties to take all practicable measures to prevent releases of controlled substances into the atmosphere, including, *inter alia*:

(a) To recover controlled substances in Annex A, Annex B and Annex C of the Protocol, for purposes of recycling, reclamation or destruction, that are contained in the following equipment during servicing and maintenance as well as prior to equipment dismantling or disposal:

(i) Stationary commercial and industrial refrigeration and air conditioning equipment;

(ii) Mobile refrigeration and mobile air-conditioning equipment;

(iii) Fire protection systems;

(iv) Cleaning machinery containing solvents;

(b) To minimize refrigerant leakage from commercial and industrial air-conditioning and refrigeration systems during manufacture, installation, operation and servicing;

(c) To destroy unneeded ozone-depleting substances where economically feasible and environmentally appropriate to do so;

5. To urge the Parties to adopt appropriate policies for export of the recycled and used substances to Parties operating under paragraph 1 of Article 5 of the Protocol, so as to avoid any adverse impact on the industries of the importing Parties, either through an excessive supply at low prices which might introduce unnecessary new uses or harm the local industries, or through an inadequate supply which might harm the user industries;

6. To request the Scientific Assessment Panel to study and report, by 31 March 1994 at the latest, through the Secretariat, on the impact on the ozone layer of continued use of recycled controlled substances and of the utilization or non-utilization of available environmentally sound alternatives/substitutes and to request the Open-ended Working Group of the Parties to consider the report and to submit their recommendations to the Sixth Meeting of the Parties;

To request the Technology and Economic Assessment Panel to review and report, by 31 March 1994 at the latest, through the Secretariat, on:

(a) The technologies for recovery, reclamation, recycling and leakage control;

(b) The quantities available for economically feasible recycling and the demand for recycled substances by all Parties;

(c) The scope for meeting the basic domestic needs of the Parties operating under paragraph 1 of Article 5 of the Protocol through recycled substances;

(d) The modalities to promote the widest possible use of alternatives/substitutes with a view to increasing their usage and release their reclaimed substances to Parties operating under paragraph 1 of Article 5 of the Protocol; and

(e) Other relevant issues and to recommend policies with respect to recovery, reclamation and recycling, keeping in mind the effective implementation of the Montreal Protocol;

8. To request the Open-Ended Working Group of the Parties to the Protocol to consider the reports of the Scientific Assessment Panel and the Technology and Economic Assessment Panel and any recommendations in this regard made by the Executive Committee and submit their recommendations to the Sixth Meeting of the Parties, in 1994;

2.0 CURRENT APPLICATIONS OF METHYL BROMIDE

2.1 General scope of use

Methyl bromide is used as a fumigant against a wide spectrum of pests, including pathogens (fungi, bacteria and soil-borne viruses), insects, mites, nematodes and rodents. These pests may be in soil, in durable or perishable commodities or in structures and transportation vehicles.

It has some features which make it a versatile and convenient material for many applications. In particular, it is quite penetrative, thus reaching pests in soil, commodities and structures often at a considerable distance from the application point of the fumigant and inaccessible to many other control measures (e.g. contact insecticides, fungicides of low volatility). Also, it is active against most pests at low concentrations, though there is a broad range of susceptibility and dosage schedules need to be adjusted accordingly. Exposures typically range from an hour up to 2 days with concentrations ranging from 10 to 150 g m^{-3} for commodities and some days with application rates of 20 to 100 g m^{-2} for soils. Exposure periods and concentrations used typically are varied within these ranges depending on system under treatment, target pest, and quarantine, contractual and other specifications and regulations.

Global sales of methyl bromide, excluding China, India and former USSR, for major use sector, are given in Table. 2.1. Many of the diverse uses of methyl bromide individually consume only small quantities of methyl bromide annually. Despite their low consumption many of these applications are currently of considerable importance with regard to quarantine or to particular industries. There are relatively few major uses of methyl bromide. However, the multitude of uses makes overall consideration of methyl bromide, as a fumigant, complex and also makes simple consideration of alternatives impossible.

Surveys were carried out by MBTOC to determine the proportion of methyl bromide used in particular applications within those sectors. Results of those surveys are given in detail in the sections of this report dealing specifically with sectors of application (Sections 4.1, 4.2, 4.3, 4.4). Major uses in 1992 with annual consumption of more than 900 tonnes per annum were:

In soil

- as a preplant treatment against insect, nematode and fungal pests and for weed control in production of cut flowers, strawberries, tobacco, curcurbits, tomatoes and peppers;
- as a replant treatment for deciduous fruit trees against 'replant disease';
- as a treatment of seed beds principally against fungi for production of seedlings, notably tobacco;
- as a treatment to ensure production of pest-free propagation stock, e.g. strawberry runners.

Table 2.1 Global sales of methyl bromide (tonnes) by use sector (China, India and former USSR not included).

Year	Soil	Post Harvest	Structural	Residential/ Commercial	Chemical Intermediates	Total Sales
1984	30,408	9,001	1,285	881	3,997	45,572
1985	33,976	7,533	1,274	983	4,507	48,273
1986	36,090	8,332	1,030	999	4,004	50,455
1987	41,349	8,708	1,763	1,160	2,710	55,690
1988	45,131	8,028	1,910	1,737	3,804	60,610
1989	47,542	8,919	2,083	1,530	2,496	62,570
1990	51,306	8,411	1,740	1,494	3,693	66,644
1991	55,079	10,290	860	957	4,071	71,257
1992	57,407	9,564	902	1,062	2,648	71,583

Data source: Methyl Bromide Global Coalition (1994)

In durables

- as a treatment against insect pests for cereal grain and similar commodities in storage to restrict damage to the commodity;
- as a treatment for cereal grain and similar commodities at point of import or export as quarantine, phytosanitary or contractual measures;
- to control pests of dried fruit and nuts in storage and trade;
- as a quarantine measure for treatment of exported or imported timber, principally against insects and some fungal pests.

In perishables

- as a phytosanitary or quarantine treatment against insect pests in many fresh fruit and vegetables in export trade.

In structures

- as a treatment for flour mills and similar premises against established insect infestations;
- as a fumigant, principally against termites, in domestic premises;
- as a treatment of ships and freight containers, either empty or containing durable cargo, against rodents and insect pests, often as a quarantine or contractual measure.

2.2 Supply of methyl bromide

Methyl bromide has a boiling point of 4°C. It is normally supplied and transported as a liquid in pressurised steel cylinders or cans. Typically the cylinders used range in size from 10 kg to 200 kg capacity. There is also trade in larger cylinders of up to 18 t capacity and in small disposable steel cans, typically of 0.4 - 1 kg capacity. Methyl bromide is usually applied directly from the cans or cylinders in which it is transported, though it may also be decanted from large cylinders from which it is then directly applied. Decanting is not permitted in some countries.

2.3 Application methods

2.3.1 Soil fumigation

Basically, MeBr is applied in one of the two following methods: manual application or mechanised injection.

2.3.1.1 **Manual application.** This method involves a surface application where the material is applied to soil which has been pre-tarped with plastic sheets. The main method in this application is the so-called 'hot gas' method, where liquid MeBr from cylinders undere pressure is vaporised in a vaporising device (heat exchanger) and then introduced under the plastic cover.

Worldwide, outside USA, this is the principal method of application and almost exclusively the only method used in fumigating soil in greenhouses (glass and plastic houses). In many countries, this method is widely used also for outdoor fumigations. In some situations, field fumigation is carried out with mulched strips (strip fumigation) of 0.80 - 1.20m wide, particularly for row crops such as cucurbits, tomatoes and peppers.

When applied from small steel cans of less than 1 kg capacity, the methyl bromide is not normally vaporised, but discharged directly from the can under its own pressure using a special opener. This can be done so as to release methyl bromide under the plastic cover without damage to the cover.

Methyl bromide is supplied as a mixture containing 2% chloropicrin (added as a warming agent) when used for manual application.

2.3.1.2 **Mechanised injection**. In this method, MeBr from cylinders is applied by injecting the fumigant to a depth of 20 - 25 cm into the soil, the treated area being simultaneously sealed by plastic sheeting (shallow injection). The process is normally carried out as a broad-acre fumigation where one sheet is glued to the previous one. However, some application is done under strips of plastic, with the edges of the strips buried by the machinery in the soil.

Another system of mechanised injection is deep placement (approx. 80 cm) of the fumigant without covering the area with plastic sheets. The deep injection of MeBr is carried out mainly prior to planting and replanting in deciduous orchards, vineyards and other plantations, mainly in U.S.A.

Mechanised injection is carried out with outdoor fumigation only, and is the dominant method in U.S.A. It is also used in some European countries, Israel, Australia and South Africa.

A variety of mixtures of MeBr and chloropicrin are used in this type of fumigation. In many situations a 2% chloropicrin in methyl bromide mixture is used, but under certain conditions, 30 - 50% chloropicrin may be included in the formulation.

Crops mentioned above under manual application are relevant to this method as well.

2.3.2 Application to commodities and structures

Methyl bromide is typically applied direct from the cylinder through a narrow bore application line (or series of lines) culminating in an atomising jet or series of jets which are designed to enhance the speed of vaporisation of the fumigant. The rate at which the liquid fumigant becomes a vapour is largely dependent on the ambient air temperature. These lines and jets are laid out either on the commodity, or throughout the structure to try to ensure an even distribution of fumigant. Alternatively, the methyl bromide is passed through a vaporiser (heat exchanger) which vaporises the fumigant before it is applied through suitably perforated distribution pipes, again laid out in such a way as to facilitate good distribution.

The dose of methyl bromide is calculated according to label, contractual, or legislative (e.g. quarantine) requirements. Then the required dose, taking into account the volume of space and weight of commodity, is applied by weighing the cylinder of liquid methyl bromide and allowing the required dose to be released.

In the case of commodities, this will vary from gastight purpose built fumigation chambers (portable and fixed) to very poorly sealed bagged stacks. In between these extremes, are ship's holds (sometimes very gas tight, but not always), freight containers (often not very gas tight), and well sealed bagged stacks with laminated sheeting (can be very gas tight).

In the case of structures, the gastightness varies from aircraft (sometimes very gastight), ship's holds, modern food factories and mills (can be very gastight) to older buildings such as many flour mills (often not very gastight and, in many cases, impossible to make more than partially gastight).

Normally, in all these situations, fumigation is carried out for a pre-determined period to try to ensure that the gas has had sufficient time to penetrate to the target organism, and that the *ct*-product needed to eradicate all stages of the pest life cycle has been achieved in the most difficult-to-penetrate part of the enclosure under treatment.

Technology exists to enable the *ct*-product to be monitored during the fumigation, and much lower doses can be utilised in many cases to achieve the same results, as with unmonitored treatments. The concentration must be measured in critical areas of the treatment enclosure, e.g. in the centre of the commodity bulk. This technology is not widely used, however, as it is normally cheaper to use more methyl bromide than to involve the use of the technology.

In structures (buildings, ships, aircraft, etc.) the same principles and application techniques apply, but the *ct*-product must be calculated in the floors, walls, machinery, etc. where deep seated and inaccessible infestation is the target, and which is normally the reason for using methyl bromide. Again, accurate monitoring, lower doses, but with the ability to add more fumigant, is increasingly becoming more widely used, rather than the still widely practiced method of over dosing to try to guarantee success.

In most countries, commodity and structural treatments are carried out with 100% methyl bromide formulations, superseding the formulation containing 2% chloropicrin, which is still in use in some regions.

2.4 Global quantities of methyl bromide used

Global sales of methyl bromide for the period 1984 - 1992 by year and region are given in Table 2.2. This data was supplied by the Methyl Bromide Global Coalition (1994) and does not include production in China, India and former USSR. These are estimated for 1992 to be 1000, 40 and 3000 t, respectively (Wang, W., S. Rajenderan, G.A. Zakladnoi, pers. comm.) giving a total global production and sale of 75,625 t and an estimated usage of 72,975 t for soil, commodity and structural fumigation.

Figure 2.1 shows the trend in global methyl bromide sales (excluding China, India and former USSR) for fumigation of soil, commodities and structures from 1984 - 1992. The figures show an approximately linear increase over this period at a rate of about 3700 t per year.

Fig. 2.1: Total global sales of methyl bromide (excluding China, India and former USSR) on an annual basis for the period 1984 to 1992 excluding feedstock uses

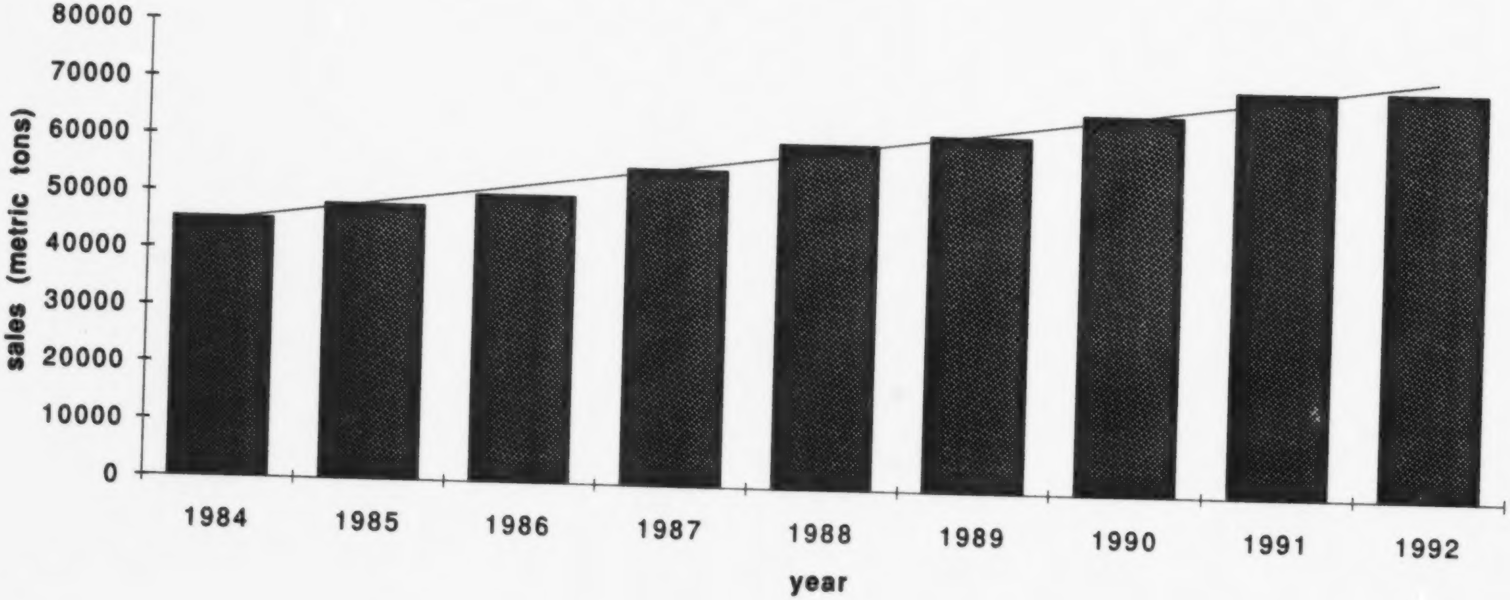

Table 2.2 Sales of methyl bromide by region, including chemical feedstock, but excluding China, India and former USSR

Year	North America	South America	Europe	North Africa	Africa	Asia	Australasia	Total Sales
1984	19,659	1,389	11,364	183	1,595	10,687	704	45,572
1985	20,062	1,503	14,414	45	1,975	9,743	531	48,273
1986	20,410	1,774	13,870	380	2,205	11,278	538	50,455
1987	23,004	1,820	15,359	385	1,751	12,816	555	55,690
1988	24,848	2,058	17,478	277	1,582	13,555	812	60,610
1989	26,083	1,701	16,952	618	2,075	14,386	755	62,570
1990	28,101	1,621	19,119	432	1,838	14,605	928	66,644
1991	30,909	2,068	17,447	1,058	2,093	16,843	842	71,260
1992	29,466	2,300	18,521	1,363	1,697	16,944	1,294	71,585

Data source: Methyl Bromide Global Coalition (1994)

Note:

Statistical regions comprised:

North America

Antigua and Barbuda, Bahamas, Barbados, Belize, Bermuda, Canada, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, El Salvador, Grenada, Guatemala, Haiti, Honduras, Mexico, Nicaragua, Panama, St. Kitts and Nevis, St. Lucia, St. Vincent & Grenadines, Trinidad and Tobago, and United States of America.

South America

Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Guayana, Netherlands Antilles, Paraguay, Peru, Suriname, Uruguay and Venezuela.

Europe

European Economic Community (E.E.C.): Belgium, Denmark, France, Germany, Greece, Ireland, Italy, Luxembourg, The Netherlands, Portugal, Spain and United Kingdom.

Other European Countries: Albania, Austria, Bosnia and Herzegovina, Bulgaria, Czechoslovakia (Czech Republic and Slovakia), Finland, Hungary, Iceland, Liechtenstein, Malta, Norway, Poland, Romania, Slovenia, Sweden and Switzerland.

North Africa, Western and North Eastern Africa

Algeria, Benin, Burkina Faso, Cape Verde, Chad, Côte d'Ivoire, Djibouti, Egypt, Ethiopia, Gambia, Ghana, Guinea, Guinea-Bissau, Kuwait, Liberia, Libya, Mali, Mauritania, Morocco, Niger, Nigeria, Qatar, Saudi Arabia, Senegal, Sierra Leone, Sudan, Togo, Tunisia, United Arab Emirates and Yemen (Republic of).

Africa, Central and Southern Africa

Angola, Botswana, Burundi, Cameroon, Central African Republic, Comoros, Congo, Equatorial Guinea, Gabon, Kenya, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Réunion, Seychelles, Somalia, South Africa, Swaziland, Uganda, Zaire, Zambia and Zimbabwe.

Asia

Afghanistan, Bahrain, Bangladesh, Belarus, China, Cyprus, India, Indonesia, Iran, Iraq, Israel, Hong Kong, Japan, Jordan, Korea (Republic of), Lebanon, Maldives, Mongolia, Nepal, Philippines, Russian Federation and former countries of USSR, Singapore, Sri Lanka, Syria, Taiwan, Thailand, Turkey and Vietnam.

Australasia

Australia, Fiji, French Polynesia, Kiribati, Micronesia, Nauru, New Zealand, Papua New Guinea, Solomon Islands, Tonga, Tuvalu, Vanuatu and Western Samoa.

Certain countries were reclassified to different regions between the 1984 and 1992 reports.

A separate set of data was obtained on global consumption of methyl bromide in 1992 through the MBTOC surveys carried out by the various MBTOC sector subcommittees. The figures obtained differ slightly from the data in Table 2.2, as shown in Table 2.3.

Table 2.3 Global methyl bromide usage (tonnes, 1992) by sector

Sector	Table 2.2 data	Survey data
Soils	57,407	50,913
Durables	9,564	9,855
Perishables	*a*	6,537
Structural	1,964	3,736
China/India/former USSR	4,040	*b*
Totals	**72,975**	**71,041**

[a] Tonnage for perishables included with durables as 'post-harvest' use.

[b] Table 2.2 data adjusted to include production tonnage for China, India and former USSR. Included in survey data as estimates of 300 t for structural and remainder for durable treatment.

The figures given in Table 2.3 differ from the two data sources, both in total and by sector. The discrepancy in total, with the survey showing 1,934t less than the sales data, is ascribable to incomplete reporting, double counting (some data in more than one category) inventory changes (i.e. annual production does not necessarily equate to consumption in any one year and uncertainties in some estimates). The differences by sector may reflect reporting of methyl bromide in different sectors in the two data sets in addition to inventory changes. Survey data obtained by MBTOC may be expected to underreport consumption globally because of lack of response from some users.

Further study is required to reconcile these figures fully. For the purposes of this report, the data presented in Table 2.2 is taken to be correct, but the proportions of use as shown in the MBTOC surveys are used where needed to scale within sector use.

2.5 Technical and legislative limitations to methyl bromide use

2.5.1 Technical limitations

Although methyl bromide is well recognised as being a most useful fumigant, there are a number of technical factors which restrict its application. Not only have these tended to limit its field of application, apart from direct economic considerations, but some have also led to legislative and other restrictions, independently of its detrimental effect on the ozone layer.

Methyl bromide can have adverse effects on a number of commodities, causing taint and odours. These are listed in Bond (1984). It also has substantial phytotoxicity. This makes it an effective weedicide in soil treatments, but can limit its usefulness in treatment of growing plants and perishables against pests, sometimes resulting in reduced storage life (e.g. of cut flowers) or preference for alternatives.

Treatments with methyl bromide result in production of bromide ion residue. These may accumulate to excessive levels in commodities that are fumigated several times and have been a cause for concern in ground water in some European countries. Production of these residues is discussed in detail in later sections of this report.

A major limitation to methyl bromide use is its toxicity to humans. Many countries restrict the actual application of methyl bromide to trained, licenced fumigators and may specify appropriate safety equipment and airing times for removal of residual gas after treatments. Additionally, there may be stringent controls on allowable concentrations in workspaces and in the environment around fumigations. The toxicity to humans has recently been reviewed in detail (Anon., in press).

2.5.2 Legislative limitations

A number of countries have current or projected legal restrictions on the use of methyl bromide. Some of these are in response to its status as an ozone-depleting substance, but others, such as in the Netherlands, were put in place in response to concerns over local environmental contamination mainly related to methyl bromide in air and to bromide in surface water.

The 1994 TEAP Report contains a summary of legislative controls on methyl bromide in various countries. Since that report, the EU, Italy, Canada, Sweden and Denmark have all increased their present or future restrictions on methyl bromide.

The European Union has adopted a new Council Regulation (EC) No 3093/94 on substances that deplete the ozone layer, in force from 23 December 1994, which introduces a 25% cut in the production and supply of methyl bromide based on 1991 levels from 1 January 1998, with an exemption for quarantine and preshipment. Canada has adopted a similar position. Article 15 of the EU Council Regulation on ODS also requires all precautionary measures practicable to be taken to prevent emissions of methyl bromide resulting from leakage from 3 months after the regulation becomes effective. Denmark is to phase out the major use area of methyl bromide (soil/tomatoes) by 1 January 1996 (about 70% of total use) and the remaining use areas by 1 January 1998 without exemptions for preshipment and quarantine (Ministry of the Environment Statutory Order No. 478, June 1994). The Nordic Environmental Strategy, adopted by the nordic countries is for phaseout of Methyl Bromide by 1 January 1998, with exemption for preshipment and quarantine uses. In Italy, a phaseout date of 1 January 1999 has been set with exemptions in exceptional circumstances (Italian Law 594/93). However, this law is not currently in force.

The Netherlands has now completed its phaseout of use of methyl bromide for soil fumigation with very restricted uses still permitted for some commodity treatments.

2.6 References

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3.0 EMISSIONS, EMISSION REDUCTION AND RECLAMATION, RECOVERY AND RECYCLING OF METHYL BROMIDE

Executive Summary

Estimates of the proportion of the applied methyl bromide released into the atmosphere from fumigation vary widely. Emissions occur inadvertantly through leakage and permeation during treatment and intentionally while venting at the end of treatments. The quantity of methyl bromide emitted from a treatment varies on an individual case basis as a result of the use pattern, the condition and nature of the fumigated materials, the degree of seal of the enclosure, and local environmental conditions. Methyl bromide is a reactive material: it is incorrect to equate production with emissions as at least part of methyl bromide applied is converted in use to non-volatile materials.

Under current usage patterns, the proportions of applied methyl bromide emitted eventually to atmosphere globally were estimated by MBTOC to be 30 - 85%, 51 - 88%, 85 - 95% and 90 - 95% of applied dosage for soil, durables, perishables and structural treatments, respectively. These figures, weighted for proportion of use and particular treatments, correspond to a range of 46 - 81% overall emission from agricultural and related uses (34,000 - 59,000 tonnes, based on 1992 sales data).

MBTOC assumed that the most energy intensive alternative to methyl bromide was use of steam heating for soil treatment. The indirect Global Warming Potential of methyl bromide, in terms of CO_2 produced, with energy required supplied electrically, was 20 kg CO_2 per tonne for synthesis and vaporisation. Using equivalent energy sources, steaming at 4 - 7 m^3 per m^2 and methyl bromide at 25 - 100 g per m^2 were equivalent to 1200 - 2100 and 5 - 20 g CO_2 per m^2. The atmospheric lifetimes of all gaseous potential alternatives to methyl bromide were too short to give appreciable direct GWP.

There are well developed containment technologies for decreasing the rate of leakage of methyl bromide from fumigation of soil, structures and commodities. These techniques are only in limited use worldwide, with their lack of adoption constrained particularly by poor dissemination of information and perceived or real increases in costs and increased logistic problems. Better containment is essential before recovery of the used methyl bromide can be considered.

Better sealing of enclosures and the use of less permeable sheeting was identified as an immediately applicable, technically proven means of substantially reducing emissions from soil, durable commodity and structural fumigation treatments, with the largest improvement coming from soil fumigation. Better containment and/or longer exposure times can lead to reduced dosage levels to achieve the required degree of control. These changes in application techniques are estimated to be able to reduce emissions substantially for the soils, durables and structural sectors respectively. Many facilities used for fumigating perishables already have a high standard of gastightness, but there is scope for improvement in others.

There is active research into the development of recovery and recycling plant for methyl bromide. There are a few special examples of recovery plant already in use and it is anticipated that prototype plant capable of recycling recaptured gas will be evaluated by the end of 1995. Some may eventually be suitable for recovery from soil fumigations, but most are directed at recovery from enclosures used for structure or commodity fumigation (currently around 10% of global use).

It is unlikely that significant demand from Article 5 countries can be met with recycled material. There is, however, potential for recycling, including in developing countries, in some specialised applications, notably treatment of perishables in gastight chambers.

Most of the potential recovery and recycling technologies are complex in nature and expensive to install compared with the cost of the fumigation facility itself. Some systems would have high running costs associated with energy requirements. Many would require a level of technical competence to operate that would not normally be found at many fumigation facilities.

It will be necessary to set specifications on equipment efficiency and tolerable levels of emission if recovery is to be recognised as an acceptable method of reducing methyl bromide emissions to the atmosphere.

3.1 Definitions

The following terms are used throughout this section and where appropriate are consistent with the definitions used in the Montreal Protocol documents.

Containment:	Securing the fumigation site so that inadvertent leakage from the treatment area does not occur during the actual fumigation treatment.
Recovery:	The collection and storage of methyl bromide from fumigation operations.
Recycling:	The re-use of methyl bromide following a basic recovery and cleaning process. Normally this would only involve 'on-site' processing.
Reclamation:	The re-processing and upgrading of recovered methyl bromide by more complex physical or chemical treatments. Often this would involve storage for subsequent re-use, either on-site or at other sites.
Destruction:	The chemical or physical destruction of methyl bromide recovered from fumigation operations.

3.2 Emissions of methyl bromide from treatments

In normal use, methyl bromide may be vented intentionally from a treatment at the end of the exposure period, it may be lost inadvertently through leakage and permeation during the exposure period, and it may be lost through desorption of sorbed material subsequent to the fumigation. Overall, the sum of the quantity of methyl bromide emitted from these processes will constitute the emission to atmosphere, unless recapture systems are in place.

A proportion of any applied dosage of methyl bromide reacts with the treated material (e.g. soil, grain, fruit) or associated structures and packing material. The end product of this reaction is typically non-volatile bromide ion, various methylated products and carbon dioxide. These have not been identified as ozone depletors. The proportion of non-volatile bromide residue formed as a result of a treatment is a direct measure of the proportion of the applied methyl bromide not emitted to atmosphere. The proportion emitted is found by difference. This 'mass balance' approach is typically used to estimate quantities of methyl bromide released to atmosphere from a treatment. It gives a conservative estimate and is simple to use as bromide ion tends to be easily detected and quantified. An allowance has to be made for natural bromide ion already present prior to treatment.

An alternative approach is to observe the quantities emitted directly. This is experimentally difficult as it relies on quantification of a number of fluxes of gas and may miss some important ones. The approach tends to underestimate the emissions, but is often used in soil fumigation studies.

The proportion of applied methyl bromide converted to fixed residues, and thus not released to atmosphere, varies widely with the particular treatment situation. It is influenced, *inter alia*, by the degree of containment (sealing, permeability of the enclosure), and temperature, moisture content and reactivity of the treated material. With soil fumigation, the mode of application, e.g. 'hot gas', deep injection, is also a major factor since it influences the contact time between the methyl bromide and substrate, and thus the opportunity for varying degrees of reaction and dispersion within the soil before loss from the system.

There is remarkably little firm quantitative field data available on production of bromide ion or other measures of loss of methyl bromide from particular systems. For the purposes of this Report, MBTOC has relied on some particular data for specific situations and estimates provided by MBTOC members. Ranges of estimates have been given. These are used to encompass both the true variability to be expected with different sites, techniques and situations, and the range of opinions expressed by experts within MBTOC. An approximation of the quantity of methyl bromide lost to atmosphere has been made by integrating this information over the total usage of methyl bromide (Table 3.1).

Table 3.1 includes estimates for emissions from four types of application to soils. The variation given in two of these is wide and reflects the range of data available to MBTOC experts. It is not possible to provide a weighting of figures within these ranges to give a precise average emission as the distribution of emissions over the global range of practice is not estimatable, because of lack of good data on the subject. However, it may well be that the true value differs substantially from average value of range quoted.

The potential range of emissions can be estimated from laboratory sorption (decomposition) studies with various soils. Table 3.2 shows a range of values of residual methyl bromide calculated on the basis of the stated half life for 3 and 7 day exposures, corresponding to medium and prolonged exposure periods in practice. It can be seen that the ranges given in Table 3.1 fall within the variation in rate of reaction in Table 3.2. Arvieu (1983) gives a similar range of reactivity.

Table 3.1 Estimated usage of methyl bromide and emissions to atmosphere for different categories of fumigation

The following table shows the amounts of methyl bromide used and the estimated percentage emitted to the atmosphere for each of the major categories of use.

Type of fumigation and commodity	**Amount used**		**Estimated emissions**		**Notes**
	(t)	**(% of global non-feedstock usage)**	**(t)**	**(%)**	
Enclosed Space (Durables)					
Grains, etc.	4601		2347 - 3221	51 - 70	*a,b*
Nuts	236		120	51	*a*
Dried Fruit	236		205	87	*a*
Timber	4782		4208	88	*a*
Subtotal	9855	12.96%	6880 - 7754	70 - 79	
Enclosed Space (Perishables)	6537	8.59%	5556 - 6210	85 - 95	*c*
Enclosed Space (Structural)	2264	2.98%	2038 - 2151	90 - 95	*d*
Soil Fumigation					
Soil injection - shallow with tarp	31000		10230 - 24800	33 - 80	*e*
Soil injection - deep with tarp	2296		689	30	*d*
Vaporised gas with tarp	22963		11481 - 19518	40 - 85	*d*
Soil injection - deep without tarp	1148		918	80	*d*
Subtotal	57407	75.47%	21022 - 45925	37 - 80	
Total agricultural usage	76063		35229 - 61773	46 - 81	
Mean emission over all categories				64	*f*

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a Calculations supporting these figures given in Annex 3.1.

b Higher emission rate estimated from residue data for bag stacks by MBTOC (Annex 3.1).

c Values estimated by MBTOC. Calculations consistent with higher figure given in Annex 3.1.

d Range of values estimated by individual MBTOC members on basis of experience and published studies.

e Low value consistent with emissions from reactive soils estimated by MBTOC, high value from data in Yagi *et al.*, (1993) corrected by Cicerone, R.J. (pers. comm.).

f MBTOC recognises that the true value of emissions may differ substantially from this mean.

Table 3.2 Half-life and % methyl bromide remaining in soil (laboratory studies) after 3 and 7 days. Calculated from data reviewed in Visser and Linders (1992)

Soil	Temperature (°C)	Moisture content	Half-life (d)	Calculated % remaining after 3d	Calculated % remaining after 7d
Clay loam	23	0.75[a]	0.2	<1	<1
Loam 1	20	0.568[b]	15.4	87	73
Loam 2	20	0.568[b]	19.8	90	78
Sandy clay loam	23	0.75[a]	1.5	25	4
Sandy loam 1	20	0.236[b]	34.7	94	87
Sandy loam 2	20	0.726[b]	17.3	89	76

[a] water activity
[b] g/g dry basis

MBTOC recognised that improvements in technique may lead to changes in percentage percentage emissions from particular methyl bromide uses and that there is continuing progress in this area. The figures given in Table 3.1 refer to 1992 estimates.

Table 3.1 figures are based on tonnages used in various sectors of application derived from estimates from the various MBTOC subcommittees. The total tonnage for agricultural and structural fumigation estimated in this way, is slightly greater than that derived from global sales estimates, presumably due to inventory changes and possibly also variation in reporting. Estimates of emissions to atmosphere for 1992 based on applying proportions estimated in Table 3.1 to global sales figures, are 34,000 to 59,000 t for agricultural and structural treatments.

3.3 Global Warming Potential and Alternatives

Some of the alternatives to methyl bromide use for particular situations, presented in this report, are gaseous, but none have long atmospheric lifetimes. There is the possibility that they can contribute directly to global warming, if they can be transferred into the stratosphere. Other alternatives are quite energy intensive, notably heat-based methods, and may contribute indirectly through CO_2 generation during the production of electricity or directly through burning of hydrocarbons and other carbonaceous material to create the required heat. Additionally, alternative chemicals will require energy for their synthesis, transportation and application.

MBTOC did not conduct an in-depth study of direct and indirect GWPs for the various proposed alternatives. It assumed that use of steam for soil sterilisation was the most energetic process amongst those being considered, so this placed an upper limit on the relative global warming associated with adoption of alternatives.

Table 3.3 shows comparative energy costing for some methyl bromide and steam treatments of soil. The data suggests an increased relative global warming potential using steam as an alternative.

Table 3.3 Relative global warming calculations for methyl bromide and steam sterilisation as an alternative soil treatment

Assumptions:
Both calculations: energy supplied by electricity and direct GWP of methyl bromide may be neglected.

(1) Methyl bromide fumigation (hot gas method):
- energy for synthesis 774 MJ t^{-1}
- energy for vaporisation 306 MJ t^{-1}

TOTAL 1080 MJ t^{-1}

For a power station generation efficiency of 33.5%:
- energy required = 3223 MJ t^{-1}

At an emission of 0.0618 kg CO2 per MJ = 203 kg CO_2 t^{-1}
At application rates of 25 - 100 g m^{-2}, energy equivalent = 5 - 20 g CO_2 m^{-2}

(2) Steam sterilisation under sheets or using negative pressure systems:
- steam consumption 4 - 7m^3 m^{-2}
- total energy equivalent 6.4 - 11.2 MJ m^{-2}

For a power station generation efficiency of 33.5%:
- energy required = 19 - 33 MJ m^{-2}

At an emission equivalent of 0.0618 kg CO_2 per MJ = 1200 - 2100 g CO_2 m^{-2}

Data sources: Methyl Bromide Global Coalition and MBTOC

3.4 Opportunities for Methyl Bromide Emission

During any fumigation operation there are three distinct opportunities for methyl bromide to be emitted to the atmosphere.

- By leakage during the actual fumigation treatment. This is undesirable from the fumigation point of view because it reduces the effectiveness of the treatment as well as having worker safety implications.
- During venting of the fumigation space immediately after fumigation or removal of the cover sheets when a deliberate discharge to the atmosphere take place.
- Following treatment when the treated soil, commodity or structure slowly emits any adsorbed methyl bromide.

For most fumigation operations venting following fumigation results in the largest discharge. Emission of adsorbed methyl bromide is the next largest followed by leakage, although this is very commodity and site dependent. The first and to some extent the third type can be controlled or reduced by better containment of the fumigation site. The second can only be controlled by recovery followed, if possible, by recycling or reclamation or by destruction.

Possibilities for emission reduction in soil, durable and perishable, treatments are further discussed in Sections 4.1.7, 4.2.13 and 4.3.7, respectively.

3.5 Containment

3.5.1 Soil Fumigation

Emissions to the atmosphere from soil fumigation can be reduced by using sheeting with a lower permeability and by improving the techniques used for sealing the edges of the sheeting. At present there are no objective test methods to determine the degree of seal achieved for methyl bromide treatments carried out under sheets for soil fumigation. Leakage control is effected by burying the edges of the fumigation sheets in the soil, but the reliability of this process varies widely with the conditions under which the fumigations are carried out, with the skills of the operator, the degree of quality control exercised and the intactness of the sheeting used. Research is in progress to limit permeation losses by employing thicker polyethylene sheets or laminated sheets incorporating other materials. There are many publications on the influence of less permeable sheeting on emissions. Table 3.4 gives some typical experimental results showing improved gasholding as a result of using less permeable sheets.

Table 3.4 Emissions from a methyl bromide fumigation of greenhouse soil using two different covers (from de Heer *et al.*, 1981).

	Saranex	**LDPE**
Exposure time (days) % emitted	5 20	5 56
Airing time (days) % emitted during airing	2 48	2 22
Total % emitted	68	78
Remaining in soil	*c*. 20	*c*. 10
Transformed by reaction	*c*. 10	*c*. 10

Further data on emission reduction from soil fumigations through containment and priorities for further research are given in Section 4.1.7.

3.5.2 Structural and Commodity Fumigation

Some level of containment is necessary to achieve effective fumigation. Increased containment, through improved gas tightness, and increasing the duration of the fumigation treatment can in many cases enable lower doses to be used, thereby reducing emissions to the atmosphere. A large proportion of the durable and perishable commodities are fumigated in temporary enclosures such as under tarpaulins. The remainder are treated in fixed enclosures such as freight containers and purpose built fumigation chambers. A minimum *ct*-product must be achieved to ensure effective fumigation. By improving the degree of gas tightness of the enclosure, lower initial doses can be used and the need for top up doses prevented. A move to more gastight or permanent enclosures, especially those equipped with circulation fans would make recovery of methyl bromide for subsequent recycling or destruction more feasible.

In a few countries there are standards of gastightness for various structures and enclosures which are treated with methyl bromide. These are applied to ensure leakage from fumigation is reduced so that methyl bromide concentrations are maintained at a level necessary for an effective treatment or for environmental or human health reasons. Table 3.5 shows standards for several countries.

Table 3.5 Examples of pressure test standards for gastightness of some fumigation enclosures and treated structures

Structure	Country	Typical pressure range (Pa)	Full or empty	Time	Reference
Bag stacks under sheets	Indonesia	-200 to -100	full	> 10 min	Nataredja and Hodges, 1990
Farm storage bins	Australia	250 - 125	empty	> 5 min	Chantler, 1984
Flour mills, churches	Germany	10 - 5	empty	> 4 sec	Reichmuth, 1993
Freight containers	Australia	200 - 100	empty	> 10 sec	Banks, 1988
Fumigation chambers	USA	500 - 50	empty	>30 sec	USDA-APHIS, 1976
Silo bins	Japan	5000 - 2000	empty	> 20 min	Takeda *et al.*, 1980
Silo bins	Australia	1000 - 500	full	> 5 min	Banks, 1984a
Storage sheds	Australia	200 - 100	full	> 5 min	Banks, H.J. (pers. comm.)

Direct emission of methyl bromide by leakage can be very significant. Permanent (non-flexible) structures achieving the highest standards shown in Table 3.5 can be expected to lose gas at a rate of up to 5% per day (Banks and Annis, 1984) although flexible (but well sealed) enclosures created by using low-permeability plastic sheeting, such as are used for carbon dioxide fumigation of rice stacks in Indonesia lose gas at less than half that rate (Annis *et al.*, 1984). After introducing very low, but measurable levels of leakage, such as that specified for flour mills in Germany, ventilation rates of several air changes per day can still occur, (two changes per day results in 86% loss by leakage).

There are techniques available for the durable sealing of buildings, such as grain stores, silos and mills, to achieve a high level of gastightness (Newman, 1990). These have been used successfully on very large structures (eg 250,000 tonne capacity grain storage sheds at Kwinana, Western Australia (Ripp, 1984), but their use is not widespread. Using a patented process, methyl bromide can also be released by heating the carbon bed electrically (Stankiewicz and Schreiner, 1993). These processes are often more effective than sheeting of structures with plastic or various temporary measures often used to prepare structures for methyl bromide treatment. Doubts are often expressed about whether increased gas tightness or sealing of complex structures such as flour mills is possible. However in several parts of the world, achievement of significant levels of sealing in such structures is being achieved (Reichmuth, 1993).

Emission reduction for treatments of durables through containment is further discussed in Section 4.2.13.

3.6 Recovery

A number of techniques have been proposed or investigated for their potential to recover or capture methyl bromide from fumigation operations. Depending on the technique used, recovery would lead to the methyl bromide either being emitted to the atmosphere at some later stage, being recycled within the fumigation facility or being destroyed. For technical or economic reasons only three recovery techniques are currently or have been in commercial use at the time of writing this report. These are adsorption onto activated carbon, condensation and absorption into reactive liquids. Several others are being actively researched. If containment and recovery are to be specified as the means of reducing methyl bromide entering the atmosphere, it will be necessary to define the maximum permissible quantity or concentration that may be emitted. This will allow specification of efficiencies required for recapture equipment.

3.6.1 Activated Carbon

Activated carbon can adsorb relatively large amounts (up to 10 - 30% by weight depending on activated carbon type and conditions) of methyl bromide. It is widely used throughout the world to remove trace amounts of organic contaminants from gas streams. For fumigation operations, a vessel containing activated carbon is installed in the gas vent line. At the end of the fumigation treatment, the gas mixture containing methyl bromide and air is passed through the activated carbon onto which the methyl bromide is adsorbed. The proportion retained on the activated carbon depends mainly on the amount of free activated carbon available and the rate at which it adsorbs depends on the concentration in the gas stream, gas flow rate, activated carbon characteristics and temperature. At low loadings recovery rates of close to 100% are achievable. However, for most systems, some methyl bromide will be emitted to the atmosphere.

Eventually the adsorption capacity of the activated carbon is reached and it needs to be regenerated or disposed of. Regeneration can be achieved by passing hot gas over the activated carbon and could be the basis of a reclamation process (see Section 3.7.2). Alternatively, the activated carbon and methyl bromide can be incinerated in a specialised facility. However concerns about emissions of toxic chemicals may prevent this from being a viable option in some areas.

Although there has been much research into the potential use of activated carbon with methyl bromide, there are only a few known commercial fumigation installations worldwide which have or have had activated carbon beds installed to recover methyl bromide. There was a 30 m^3 chamber in Belgium which is no longer in use. There are five 30 m^3 chambers in the Netherlands (one transportable) each with a 70 kg filter of activated carbon. Fumigation at 30 g m^{-3} is carried out and a 40 - 50% recovery is achieved. The activated carbon lasts for 40 fumigation operations and the spent carbon containing the adsorbed methyl bromide is incinerated in a special incineration facility. There is also a 30 m^3 chamber in Thailand fitted with a 72 kg bed of activated carbon. The chamber is used for fumigating asparagus and green okra exported to Japan. The system is capable of reducing methyl bromide concentrations in the vented gas to 5 ppm within 30 minutes. The fully absorbed activated carbon is disposed of in a sanitary land-fill. Italy is reported to require activated carbon scrubbing systems on fumigation installations to reduce the potential hazard to workers and the public. It has not been possible to verify whether they are in use and whether this includes non-chamber fumigation.

An activated carbon system has also been developed by Rentokil UK for use with their fumigation bubble, a well sealed plastic tent enclosure used for fumigation of small structures. A 10 kg activated carbon bed which can hold up to 1.5 kg methyl bromide (equivalent to 5 fumigations) is used. Regeneration of the activated carbon is achieved by blowing hot air through the beds. This results in direct emission to the atmosphere. However, its use was intended only to prevent emissions that might endanger people in the immediate vicinity of the fumigation operation not as a means of emission prevention.

Although activated carbon systems provide the most immediate potential for reducing methyl bromide emissions, they have usually only been considered for very small facilities where commodities or structures are fumigated and where, for reasons of protecting the immediate surroundings, very low concentrations of methyl bromide are permitted. Very large activated carbon beds containing tonnage quantities of carbon would be required for the fumigation of large structures or enclosures such as mills, grain silos or tarpaulin fumigation. However, in October 1994 trials were carried out in a mill in Germany using activated carbon to recover and recycle methyl bromide. Further information on this plant is given in Section 3.7.2. In all situations, once the activated carbon has been fully loaded it will be necessary to remove the carbon for disposal or regeneration in an appropriate manner. While this is by no means impossible, there are regulatory implications associated with the transportation and storage of toxic materials.

3.6.2 Condensation/activated carbon

A system is in operation in California, USA which uses a method of condensation to recover methyl bromide followed by removal of residual trace quantities with an activated carbon bed. This plant directly recycles the methyl bromide and is more fully described in Section 3.7.1.

3.6.3 Absorption into reactive liquids

Amines typically react with methyl bromide to give methylated non-volatile products. A system based on organic amines and alkali for removing residual methyl bromide from fumigated 28 m^3 freight containers in Russia has been described (Rozvaga and Bakhishev, 1982). No information was available to MBTOC on whether this system is in current use. See Section 3.6.5 for additional information on this technique. Mordkovich *et al.*, (1985) have also described a technique using aqueous sodium sulphite as a neutraliser and a mixture of ethylene diamine and sodium carbonate as an adsorbent. Again, it is not known whether these techniques have achieved general use.

3.6.4 Adsorption onto zeolite

Processes based on the use of zeolite adsorbents to remove CFCs from vented air streams are in commercial use. Work is well advanced on the development of this process for methyl bromide, both for recovery and for recycling (Nagji and Veljovic, 1994a). Although zeolites are more expensive than activated carbon, they have high adsorptive capacity, particularly at low concentrations. They can be manufactured to very narrow pore size distribution tolerances for specific applications and it may be possible to avoid any potential problems of contamination of the recovered methyl bromide with other volatile compounds by utilising the selective sorption that is conferred by a particular pore size range. Pilot scale demonstration trials of the process were carried out in July 1994 to demonstrate the technical feasibility of the technique. Recovery in excess of 90% was achieved (Nagji and Veljovic, 1994b). Analysis of the recycled methyl bromide from cherry fumigation showed no other volatile compounds from the fruit were released. However, these tests need to be confirmed over a large number of adsorption/desorption cycles. The Port of San Diego Authority have announced a decision to install, in early 1995, a full size prototype plant based on adsorption of zeolite to reduce methyl bromide emissions from a 2,100 m^3 quarantine chamber.

3.6.5 Techniques under development

- Improved solid absorbants

  Research in Japan has led to the development of a new adsorbent, MBAC, which is a mixture of activated carbon and special substances (amines) which has a greater adsorptive capacity for methyl bromide than activated carbon alone. This material can be produced as sheets and introduced into packaging to recover the slowly desorbing methyl bromide from fumigated commodities and also has potential to recover some methyl bromide from soil fumigations. The Japan Methyl Bromide Industries Association is currently conducting evaluation tests (Muraoka T., pers. comm.). There are no details yet on techniques for disposing of the contaminated adsorbent.

- Separation by refrigeration and condensation

  Because of the low methyl bromide concentration in vented gases and its low boiling point this option has been considered too complex and expensive for recovery of methyl bromide from fumigation operations, although it is used to recover methyl bromide at installations where pure methyl bromide is dispensed from bulk containers into smaller ones for direct use.

- Absorption into a liquid (gas/liquid scrubbing)

  Research was carried out in the 1970s into a technique of liquid scrubbing to remove methyl bromide from fumigation operations (Anon., 1976a). The process was developed and tested on timber fumigation under stacks and consisted of equipment to circulate methyl bromide and air from the fumigation enclosure through a tank of aqueous monoethanolamine (50%) and back to the fumigation tent. The process achieved 70% reduction in methyl bromide concentrations, but was slow taking 40 - 60 minutes to achieve this level of reduction. The size of the necessary equipment for full scale operation and the difficulties of handling the contaminated liquid material have prevented its further commercial development.

- Ozone treatment/activated carbon

  A system is under development in California, USA to use ozonation to directly destroy methyl bromide in the vented gas stream from a chamber fumigation operation. The treated vent gas would then be passed through an activated carbon bed to further remove further unreacted methyl bromide. This process has been tested on a pilot scale and a full scale plant with a target recovery of 90% is expected to be installed soon. The process will produce activated carbon contaminated with methyl bromide breakdown products. At this stage it is not known if these will present disposal difficulties.

- Direct combustion and catalytic destruction

  Research was also carried out in Japan in the 1970s into a direct combustion method and a catalytic cracking method for destroying methyl bromide in the vent gas stream from chamber fumigations (Anon., 1976b). Large pilot plants were built to test the techniques, but neither method proceeded to full size installation. The processes were effective at reducing the concentration in vent gas streams down to ppm levels but were not further developed because of the high cost, their unsuitability for stack fumigations (i.e. not transportable), concerns about the use of direct heat when methyl bromide can (under very restricted conditions) form an explosive mixture with air and the difficulties of handling the products of destruction (HBr and Br_2).

3.7 Reclamation and recycling

3.7.1 Condensation/activated carbon

There is a facility where methyl bromide is now reclaimed and recycled using a condensation/activated carbon process. This facility, located in Los Angeles, has two vacuum chambers which were retrofitted with a recovery/recycle plant. At the completion of each fumigation operation, the remaining methyl bromide is diluted by the addition of air from a single airwash. This diluted mixture is then drawn through vessels where liquid nitrogen cools and condenses most of the methyl bromide. The remaining methyl bromide and air is passed through an activated carbon bed where most of the remaining methyl bromide is adsorbed. Periodically the activated carbon bed is isolated and undergoes a pressure swing desorption. The plant is designed to recover 98% of the methyl bromide available for capture. The process is computer controlled. The plant was installed in late 1993, but because the fumigation chambers have not been in steady operation since then has only gone through approximately 30 recovery cycles. The capital cost and operating costs are not available, nor are figures for the effectiveness of operation.

3.7.2 Activated carbon

It is technically possible to recycle methyl bromide adsorbed on activated carbon by heating the carbon, traditionally by passing hot air over it or altering the pressure (temperature and pressure swing adsorption). Circulating air strips the desorbed methyl bromide from the activated carbon and the mixture can potentially be reintroduced into the fumigation chamber. The methyl bromide is reclaimed as a high concentration mixture in air suitable for direct reuse as a fumigant, but some topping up will be necessary to compensate for system losses so as to achieve a satisfactory fumigation concentration. Pilot scale studies have demonstrated the technical feasibility of such a process (Smith, 1992) with up to 95% of the recoverable methyl bromide being available for direct reuse. The technique has not yet been demonstrated on commodity fumigation where the build up of other gas phase impurities, if any, may be of concern both from product quality and regulatory view points. In Germany, a mill has been equiped with a recycle system based on temperature swing adsorption on activated carbon

(Stankiewicz and Schreiner, 1993). This transportable recycle system has some extra features in that it has an enrichment step to obtain high concentration and also condensation. This reduces the size and transportation effort and enables high concentrations during the recycle desorption even when the concentration in the extracted air at the end of the recovery is low. For some configurations, nitrogen will be used as the desorption gas to avoid potential explosive methyl bromide and air mixtures.

This technique could also be used for soil fumigation operations (open field or glasshouse with sheeting). In this case desorption with recycling is achieved by a combination temperature/pressure swing adsorption could be carried out using heating by direct electrical resistance. This avoids the use of excessive diluting air. Both these process steps have already been successfully used to recover CFC-11 and for cleaning exhaust air from soil clean-up to remove volatile organic compounds (VOCs) from soil (Schreiner, H., pers. comm.). The prototype plant for recovery of methyl bromide from mill fumigation operations was commissioned in September 1994. The mill has a volume of 35,000 m^3. A recovery of 97% of methyl bromide remaining after fumigation was achieved. Of this, 93.5% was available for recycling.

3.7.3 Zeolite

The recovery process based on the use of a zeolite adsorbent described in Section 3.6.4 above shows equal promise. Recycling rates in excess of 96% of that recovered have been achieved in preliminary trials (Nagji and Veljovic, 1994b).

3.8 Constraints

Most of the recovery technologies mentioned in Section 3.7 and all the recycling technologies described in Section 3.7 are complex in nature. They are likely to be relatively expensive to install compared with the cost of the fumigation facility itself and in some instances may be more expensive. Some systems would have high operating costs associated with the energy needed. Many would require a level of technical competence to operate that would not normally be found at many fumigation facilities.

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Annex 3.1

Calculation of % emission of methyl bromide from treatments using the mass balance approach

1. Derivation of formula

- Consider an enclosure containing product at density, ρ, in $t\ m^{-3}$ with an applied dosage of C_0 $g\ m^{-3}$ MeBr.
- If all the methyl bromide is converted into bromide, the resulting residue (X) will be:

$$X = \frac{C_0}{\rho} \times 0.85\ g\ t^{-1}\ \text{(ppm w/w)}$$

(0.85 factor converts MeBr to Br^- by mass)

- If the actual residue is x $g\ t^{-1}$, then the percentage not converted, and assumed to be emitted to atmosphere is given by:

$$[X - x] * \frac{100}{X}\ \% \qquad (1)$$

2. Calculation of emission of methyl bromide from bulk and bag stack treatments of grain

The average emissions from bulk grain treatments under recirculatory treatment with methyl bromide on import into Japan were calculated according to Equation (1) and used to give an estimate of emissions from bulk grain fumigation generally (Table 3.6).

Table 3.6 Fumigation of cereal grains on import into Japan (1992 data) with calculated emissions of methyl bromide based on bromide ion residue levels in commodity after treatment. Data source: A. Tateya, MAFF, Japan

Commodity	Quantity fumigated (t)	Methyl bromide applied (kg)	Estimated quantity MeBr residue level ($mg\ kg^{-1}$)	Equivalent methyl bromide residue (kg)	% emitted[a]
Wheat	910,597	55,996	20	18,212	67.5
Buckwheat	21,403	1,316	50	1,070	18.7
Maize	11,056,507	679,903	30	331,695	51.2
Other grains	2,616,647	160,907	33	86,349	46.3
Totals	**14,605,154**	**898,122**	-	**437,326**	**51.3**

[a] Calculated as 100(1-(methyl bromide residue/methyl bromide applied))

Typical residues of bromide in bag stack treatments of cereal grain are in the 5 - 10 $g\ t^{-1}$ region per application. Actual residues will vary substantially with proficiency of the treatment and the nature and state of the commodity. For the purposes of this Report, the following were assumed: product density of 0.7 $t\ m^{-3}$, dosage of 24 $g\ m^{-3}$ methyl bromide and residue of 8.5 $g\ t^{-1}$ bromide (MBTOC estimates).

On the basis of equation (1), calculated emission: 70%.

3. Calculation of methyl bromide emissions from treatment of dried fruits and nuts

3.1 Dried fruits

In a typical fumigation, product density is 0.37 $t\ m^{-3}$. For a dosage of 24 $g\ m^{-3}$ over 24h plus 24h a typical residue is 5 $g\ t^{-1}$ bromide ion with 4 $g\ t^{-1}$ 'organic' bromide, i.e. undesorbed methyl bromide. Assuming 60% of the organic bromide reacts to give bromide ion while 40% is desorbed as methyl bromide, expected residue from the treatment is 7.4 $g\ t^{-1}$ (MBTOC estimates).

On the basis of equation (1), this is equivalent to a total release of 87% and a release of 68% after the initial 24 h of airing.

3.2 Nuts

In a typical fumigation, product density is 0.34 t m^{-3}. For a dosage of 56 g m^{-3}, over 24h plus 24h aeration, a typical residue is 40 g t^{-1} bromide ion plus 48 g t^{-1} organic bromide. Assuming 60% of the organic bromide reacts and 40% desorbs on further airing, total expected residue from the treatment is 69 g t^{-1} (MBTOC estimates).

On the basis of equation (1) this is equivalent to a total release of 51% and a release of 36% after the initial 24h of airing.

4. Calculation of methyl bromide emissions from treatment of perishables

4.1 Nectarines

A fumigation of nectarines (Hinsch *et al.*, 1992) at a product density of 0.18 t m^{-3} and at a dosage rate of 48 g m^{-3} methyl bromide over 2h resulted in a bromide residue of about 6 g t^{-1} with a natural level of <2 g t^{-1}.

On the basis of 4 g t^{-1} residue, equation (1) gives an emission of 98%.

Figures of 85 - 95% emissions from perishables were adopted by the Committee since typical fumigations are likely to be performed at higher product density and with more reactive product, both tending to lower emission percentage. The March 1994 TEAP report gives lower estimates of emissions for perishables, but these figures do not take into account slow desorption of sorbed material and only give recoverable methyl bromide (i.e. free space concentration) at the end of the fumigation period.

5. Sample calculations for emissions of methyl bromide resulting from fumigation of timber (logs) in the hold of a ship prior to import into Japan (data source: A. Tateya, MAFF, Japan)

(1)	Volume of hold	7,508 m^3
(2)	Volume of logs	4,085 m^3
(3)	Space volume [(1) - (2)]	3,423 m^3
(4)	Dosage	25.0 g m^{-3}
(5)	Total dose [(1) * (4)]	187.7kg
(6)	Observed final gas concentration	31.7 g m^{-3}
(7)	Gas in free space at end of treatment [(6) * (3)]	108.5 kg

(8) Therefore, gas vented at the end of fumigation as % of total dose, assuming no desorption:

$$\frac{(7)}{(5)} * 100 = 57.8\%$$

(9) Methyl bromide residue in the timber.

(9.1) Timber weight at apparent specific gravity of 0.9 t m^{-3} [(2) * 0.9]
= 3676 t

(9.2) On the basis of inorganic bromide residue of 5 g t^{-1} produced in the timber, weight of residual inorganic bromide is:

3676 * 5 = 18,380g

(9.3) Converting this to equivalent methyl bromide on basis of molecular weights.
Methyl bromide lost $= \frac{18{,}380}{1000} * \frac{95}{80}$

= 21.8 kg

(10) Thus, the total emission of methyl bromide is given by:

(5) - (9.3) = 187.7 - 21.8 = 165.9 kg

(11) Total % emission of methyl bromide fumigation from timber in this case:

$$\frac{(10)}{(5)} * 100 = \frac{165.9 * 100}{187.7} = \underline{88.4\%}$$

Data from nine holds (2 ships) gave about 88% emission of applied methyl bromide on the basis of the same method of calculation. Treatment at approx. 23°C and 25 g m^{-3} application rate.

4.0 ALTERNATIVES TO METHYL BROMIDE

4.1 Alternatives for soil treatment

Executive Summary

On a global basis, the major use of methyl bromide is as a preplant soil fumigant to enhance crop productivity in locations where a broad complex of soilborne pests, including plant pathogenic fungi, bacteria, viruses, nematodes, arthropods and weeds, otherwise limit economic production of certain crops. However, methyl bromide is a toxic fumigant of environmental concern which has been used successfully under a wide variety of conditions and cropping systems.

Soil fumigation with methyl bromide has been successfully replaced in some areas by methods and techniques that have been available for many years but that have been adapted or modified to suit local requirements. Alternatives used in such systems, as well as potential alternatives used or under study in other crops, are discussed in this report. None of the specific alternative methods discussed here, used alone, have the broad spectrum of activity, efficacy or consistency of methyl bromide. For some situations there may not be adequate alternatives for methyl bromide. The development of a comparable agricultural system without the use of methyl bromide, in many cases, will require the integration of multiple alternative technologies and extensive research to achieve a similar spectrum of efficacy and reliability.

To implement alternatives to methyl bromide, an integrated pest management (IPM) strategy will be required. IPM utilises pest monitoring techniques, establishment of pest injury levels, and a mix of strategies and tactics to prevent or manage pest problems in an environmentally sound and cost-effective manner. This approach to managing pests is needed to avoid future environmental problems associated with soilborne pest control.

Non-chemical alternatives to methyl bromide

Cultural practices are alternatives to methyl bromide but are not equally effective for all pests, cropping systems, or locations. A significant commitment to applied research and technology transfer programs will be needed to take full advantage of cultural practices in alternative cropping systems.

- **Artificial plant growth substrates** such as rock wool, allow culturing of crops without soil fumigation. Use of substrates is technically and economically feasible in greenhouses and in open fields, under suitable climatic and economic conditions. This technique has completely replaced methyl bromide in greenhouse culture in The Netherlands.

- **Crop rotations** of non pest-susceptible cultivated plants with agronomic and horticultural crops are effective in controlling many soilborne pests on crops in various parts of the world. It is possible to increase pest suppressiveness by including within rotations plants, such as oilseed rape, that are inhibitory to some plant pests. Limitations to this alternative are availability of land, persistent pest inoculum, appropriate rotational crops, equipment, expertise, and socio-economical considerations. Research on and implementation of alternatives to methyl bromide must address these factors in addition to the technical options.

- **Timing of planting** to coincide with low pest density and/or environmental conditions unsuited to activity of soil pests can be used to prevent pest damage. Use of this technique may be limited in crops with inflexible marketing and production windows.

- **Deep ploughing** can reduce pathogen inoculum through burial of pathogens and stimulation of microbial antagonists.

- **Flooding/water management** can be used to control some soilborne pests in suitable areas.

- **Fallowing** involves taking land out of production to deny pests the host or substrate needed for survival. It is a common technique in many parts of the world, but its use is limited in areas with high land values, shortages of agricultural land or when pests can survive prolonged fallow periods.

- **Cover crops** are non-commercial plantings of various plant species which are grown and turned back into the soil as green or dry residues. Their decomposition stimulates activity of micro-organisms antagonistic to soilborne plant pests. Cover crops must be designed into the cropping system so that they do not compete with the commercial crop.

- **Fertilisation and plant nutrition** manipulations can reduce or suppress some soilborne pathogens and nematodes by stimulating antagonistic microorganisms, increasing resistance of host plants, or other mechanisms.

- **Living mulches** such as miniature brassicas or clovers grown with the main crop can suppress weeds and reduce insect pests without reducing yields in some cropping systems.

- **Plant breeding and grafting**. Cultivars resistant or tolerant to single or limited number of specific pathogens (and races) are available for many crop species. In most cases new cultivars can be developed through plant breeding techniques to address specific pest problems. Plant breeding is a permanent component of crop production but it is currently very difficult to develop cultivars resistant to several pathogens. Frequently the planting of a cultivar resistant to a limited number of pests results in increased damage from pests to which it is susceptible. Grafting of susceptible annual or perennial crops on resistant rootstocks is possible for some crop species. In some cases, grafting techniques can economically and efficiently permit production without the need for soil fumigation.

Biological control is the use of an antagonistic, predatory or protective organism to control a target pest(s). There are cropping systems which have successfully used biological control agents. Generally, the spectrum of activity and host specificity of biocontrol agents is very narrow, and efficacy varies under different cultural conditions. A limited number of commercial preparations are currently available, and more are undergoing field trials.

Organic amendments such as composts, sewage, by-products from agriculture, forest and food industries may be used to control certain soilborne pests in various crops. Their application will be localised and dependent on reliable sources of raw materials for conversion into useful formulations.

Physical methods

- **Soil solarisation**, the covering of moist soil with clear plastic to increase soil temperature to lethal levels, provides opportunities for control of some soil pests. Solarisation is effective when suitable environmental conditions prevail. Its pest control efficacy can be improved by integrating it with other pest-control strategies.

- **Steam** is as effective as methyl bromide for control of soilborne pests. Energy costs, capital investments, and some specific soil types are limitations.

- **Superheated** or **hot water** may have the potential for control of weeds, soilborne pathogens and arthropods but their use is limited.

- **Wavelength-selective plastic mulches** provide the dual benefits of excluding photosynthetic lightwaves, thus preventing weed germination, while allowing heat-generating lightwaves to reach the soil, thus enhancing plant growth. These mulches are in use in many annual row crops, and transition to their use should be feasible in methyl bromide-treated crops such as tomatoes and strawberries where other types of plastic mulches are already a component of the cropping system.

- **Other physical methods** based on the use of microwave irradiation technologies and low temperatures may have potential for development of management techniques designed for specific pests and production systems. Considerable research will be needed to explore these alternatives to determine their potential.

Chemical alternatives

A number of potential alternative chemicals have been identified. They include fumigants and non-fumigants. However, many of them are under study for their potential to cause negative health effects as well as environmental contamination. It is very likely that regulatory restrictions on use of agrochemicals will increase, and chemical treatments against agricultural pests will be problematic and involve additional time and expenditures.

Available fumigant chemicals

- **Methylisothiocyanate** (MITC) and compounds which generate MITC are highly effective for control of some soil pests. The compounds are highly dependent on soil preparation and moisture for activation and uniform distribution.

- **Halogenated hydrocarbons** have been used successfully for the production of crops under the same cultural conditions in which methyl bromide is now used. However, the movement of these compounds is slower than that of methyl bromide, requiring longer aeration and dissipation times following soil fumigation. For field applications, halogenated hydrocarbons can be applied with few modifications using the same equipment that is used for methyl bromide. For pests on which they are effective, their performance is relatively consistent.

- **Mixtures**. Mixtures of soil fumigants may provide a spectrum of control approaching that of methyl bromide. These combination products may represent the most efficacious short-term alternatives to methyl bromide. A constraint for preformulated mixtures is the lack of data for registration purposes.

Non-fumigant chemicals

Control of individual soilborne pests approximating that of methyl bromide may be achieved in some cases through the use of combinations of non-fumigant materials (e.g. nematicides, fungicides, herbicides and insecticides).

Several non-fumigant chemicals have been detected in ground water under certain conditions and/or have health and safety limitations.

Non-fumigant alternatives are especially problematic due to the ability of many soil pests to develop resistance or the potential of microflora to decompose these compounds. Their regulatory status, health and environmental effects may limit their use and availability.

Other chemicals

There are additional chemicals which require further research to determine their use as alternatives for methyl bromide. Some were previously used with varying degrees of success (e.g., anhydrous ammonia, formaldehyde, carbon bisulphide, inorganic azides). Renewed interest and research may lead to re-establishment of some of these pesticides as viable tools.

Emission reductions

For an immediate reduction in atmospheric emissions of methyl bromide, plastic films with improved barrier properties to permit reduced application rates without loss in pest control efficacy can be used. Currently these films are available in many countries but they are more expensive than conventional polyethylene film.

Improvements in application technology and reduced application frequency result in immediate reductions of methyl bromide emissions.

Constraints

Since there is no single substitute for methyl bromide, multiple IPM strategies and tactics, used simultaneously are required. Each strategy or tactic may have constraints, but the package of approaches can be tailored to specific sites and situations to provide effective pest management under many conditions. In this context, constraints are viewed as indicating research gaps and should receive priority attention. Research to overcome constraints should focus not only on agricultural and ecological considerations, but also socio-economic and political parameters. The methods for overcoming the constraints are discussed.

Research agenda

The primary goal of the research agenda is to develop least-toxic alternative methods and cropping systems that are both cost-effective and environmentally sound. Existing and potential alternatives are identified in this report. Most will require applied research to adapt them to specific agronomic, regulatory, market, and other conditions in various locations.

Research emphasis in the short term (2-5 years) should be placed on documenting existing alternatives and on technology transfer.

Long-term research (5+ years) should emphasise multi-disciplinary efforts to develop integrated pest management methods and cropping systems suited to local ecosystems.

4.1.1 Introduction

Crops grown in soil are susceptible to soilborne pathogens (fungi, viruses and bacteria), nematodes, arthropods and weeds. Cultural practices such as crop rotation, organic amendments, and soil fallow are ancient methods which have been, and still are, used with varying degrees of success to deal with these problems. However, because the evolution of intensive production systems has led to an increase in damage from soil pests, more effective and/or reliable integrated pest management techniques are required.

Current management systems include use of biological agents and cultural practices, physical methods, fumigants, non-fumigants. Soil fumigation with methyl bromide, which has been used since the 1940s, can be viewed as a disinfestation technique - a method for treatment of a wide spectrum of soil pests prior to planting (Martin and Woodcock, 1983). Because of its physical and chemical properties, methyl bromide is used in many geographical regions of the world encompassing many soil types and climates. The widespread use of this fumigant has been encouraged by its simple application systems and technology. The major advantages of methyl bromide use can be summarised as: 1. rapid and consistent action; 2. the spectrum of activity against soil pests is wider than any other known soil treatment except steam; 3. no known pest resistance in the field; 4. very effective at penetrating soil; 5. can be used in soils with a wider range of moisture contents and temperatures than some other chemical treatments; 6. dissipates quickly after treatment; 7. unlike other fumigants, methyl bromide is an effective viricide. However, there are a number of disadvantages which have restricted its use (Anon., 1980, in press; Canton *et al.*, 1983; Hamaker *et al.*, 1983; de Heer *et al.*, 1986; Wegman *et al.*,

1981, 1983; van Wambeke *et al.*, 1992; United Nations Environment Programme, 1991, 1992; Yagi *et al.*, 1993) and the major ones are: 1. high toxicity and volatility make protective measures for workers critical; 2. reduces soil biodiversity; 3. bromide residues are formed in the soil which may be problematic in some crops and for some countries; 4. air pollution in neighbouring areas; 5. water contamination may occur in areas with high water tables; 6. disposal problems of plastics used to contain the fumigant during treatments; 7. classified as an ozone-depletor.

4.1.2 Existing uses of methyl bromide

Major uses: Annex 4.1.1 summarises data on worldwide use of methyl bromide as a soil fumigant. MBTOC received information on soil fumigation uses for 48 countries, representing approximately 89 percent of global methyl bromide soil use. The information used was based on responses to a survey distributed to signatory countries to the Protocol, and industry estimates. Of the countries which responded, those responsible for the greatest use of methyl bromide as a soil fumigant include the United States, Italy, Japan, Spain, Israel, France, Brazil, Turkey and Greece. Soil fumigation with methyl bromide is greatest by volume for the following crops: tomatoes, strawberries, cucurbits, nursery crops, peppers, tobacco, replant vineyards and orchards, and flowers.

Significant pest species. The broad spectrum of activities of methyl bromide against pests does not permit exhaustive enumeration of all species and countries in which the compound is used. Annex 4.1.2 presents a list of the main pest species which are controlled by methyl bromide. The Annex contains data pertaining to countries and areas of the world where methyl bromide is used for soil fumigation.

4.1.2.1 Application of methyl bromide

The high vapour pressure of methyl bromide makes necessary the use of some barrier to prevent its rapid dissipation from soil into the atmosphere following application (Kolbezen *et al.*, 1974; Munnecke and van Gundy, 1979; Rodríguez-Kábana *et al.*, 1977). This is done mainly by the use of plastic covers or less commonly by deep injection into the soil (Rodríguez-Kábana *et al.*, 1987b) followed by compacting the upper soil layer using a roller and/or "water sealing", i.e., wetting surface layer of the soil to reduce escape into the atmosphere.

When plastic covers are used, methyl bromide is injected into the upper soil layers through hollow shanks prior to covering, or is distributed under the plastic as pressurised gas by a manifold pipe system to assure uniform distribution. There are also other methods of applying methyl bromide that do not use mechanical means of application. For example, cans containing methyl bromide can be placed below plastic covers and then punctured or the gas can be dispensed through a tube inserted at various locations through the cover. The latter practices can result in greater emissions to the atmosphere if not properly covered and sealed.

In replant operations in California and other U.S.A. states, methyl bromide is injected into soil through hollow shanks to depths of 20-70 cm followed immediately by covering with plastic or by compaction of the soil surface.

Movement and distribution of methyl bromide in the soil is by gravity and diffusion (methyl bromide vapour is three times heavier than air) (Munnecke and van Gundy, 1979). Good soil preparation is essential for optimal distribution of the vapour through the soil. The soil should be free of large clods, undecomposed plant residues or other materials that hinder its movement and penetration. Soil moisture should ideally be kept at approximately 70% of field capacity. Pre-irrigation is recommended to enhance germination of weed seeds. Soil temperatures should be above 7°C.

Studies in the United States and western Europe indicate that from 20 to 85% of the methyl bromide applied to soil could be released to the atmosphere (Bakker, 1993; de Heer *et al.*, 1983; Hamaker *et al.*, 1983). The amount emitted depends on the method of application and skills of the applicator, type and quality of sealing, sealing period, dosage, soil preparation, soil type, soil moisture, air movement, and temperature (Cuany and Arvieu, 1983; de Heer *et al.*, 1983; van Wambeke, 1983, 1989b; van Wambeke *et al.*, 1974).

4.1.3 Training and worker protection

Because of methyl bromide's toxicity and its physical and chemical properties, avoidance of exposure requires comprehensive training. Workers must be aware of regulations in their country and equipped to follow handling requirements for protection. This will help reduce accidental release and exposure during applications. In North America, Japan, and Europe, workers are usually trained and regulated, but in some developing countries, methyl bromide's use is unregulated or regulations are not enforced. Safe methyl bromide handling requires development of adequate government regulations and investment in comprehensive worker training (see discussion for current uses of methyl bromide).

4.1.4 Soil pest management strategies

Key elements in considering alternatives to methyl bromide are: (a) the need for extensive research to document existing alternatives and expand the knowledge base on new alternatives; (b) an extensive program to transfer technology to growers, extension agents, pest control consultants; (c) a commitment from policy makers to create or strengthen the institutional support systems crucial to this effort. This is particularly important since there is a greater body of experience on the use of methyl bromide than on alternatives which makes its replacement difficult.

Methyl bromide is successfully used in the production of propagation material, e.g. bulbs and seedlings in nurseries, to assure pest free material and avoid dissemination of pests into non-infested lands. In such cases, methyl bromide should be replaced by highly effective methods to assure similar level of efficacy in pest control and prevent spread of pests to new areas. Additionally perennial crops (trees and vines) as compared to annual crops are planted in the same location for many years, they are deep rooted with most pest problems occurring deeper in the soil, and the breeding cycles for the pests have generally longer time frames than those of annual crops. It is therefore essential that propagation materials for perennials be as clean and free of pests as possible.

Alternatives to methyl bromide may be based on the use of other chemicals or on non-chemical methods. It is not anticipated that any single chemical or non-chemical treatment listed here will alone substitute for methyl bromide. However, in most cases, a combination of these methods, tailored to specific crops, sites, and other variables, can be, and in some cases are being used in place of methyl bromide (see Case histories 4.1.1 - 4.1.6). For example, in the decade 1981 to 1991, The Netherlands and Germany completely eliminated use of methyl bromide in soil fumigation (Anon., 1992; Mus and Huygen, 1992). This was accomplished by employing an integration of non-chemical alternatives such as improved steam sterilisation techniques, artificial and natural growth substrates, resistant plant species, crop rotation, and chemical substitutes such as metham-sodium, dazomet, and 1,3-dichloropropene (Anon., 1992).

One strategy for eliminating methyl bromide use against soil-dwelling pests is to utilise Integrated Pest Management (IPM) approach for crop protection (Franco *et al.*, 1993; Pimentel, 1981). IPM programs utilise pest monitoring techniques to detect pest presence and determine economic thresholds that warrant treatment. When treatment is needed, a mix of strategies and tactics is used to prevent and manage pest problems in an environmentally sound and cost effective manner. This approach to managing soil pests is needed to avoid future environmental problems associated with management of soils pests.

4.1.4.1. Monitoring and pest detection. Because of the broad spectrum activity of methyl bromide, the pest complexes which impact crop production in the absence of methyl bromide are sometimes unknown or poorly understood. The first component of an IPM program is to identify pests and natural enemies. The next step is to monitor populations of these organisms. From these data a pest "injury level" or "economic threshold" can be established. Treatment, using a combination of controls, occurs only when pest numbers threaten to reach the injury level. It is possible, however, to have pests not detected by monitoring to increase to levels during crop growth that cause significant crop loss.

A number of commercial techniques exist to facilitate accurate monitoring of some soil-dwelling pests (insects, mites, nematodes, pathogens, viruses, and weeds). These include ELISA (Enzyme-linked Immuno Sorbent Assay) tests for detecting soil pathogenic fungi, viruses, and phytoparasitic nematodes; a variety of traps and surfactant drenches to detect insect and mites; and seed sampling to detect weeds. More widespread use of such monitoring methods will pinpoint more precisely if and when pest populations are at levels requiring treatment, reduce unnecessary treatments of any type, and increase use of spot treatments rather than broad-scale applications over entire crops. These monitoring and economic threshold systems are well developed for some key insect, mite and nematode pests, but are either non-existent or at an early stage of development for some plant pathogens. Further research is necessary to develop and improve comparable monitoring and economic thresholds for plant pathogens. Research is also necessary to determine the presence and importance of natural enemies.

4.1.5 Soil pest management alternatives to methyl bromide

Because of its versatility, there is no single alternative chemical treatment or combination of treatments that can substitute methyl bromide in all its many uses in soil fumigation. It is possible however, to consider alternative chemicals and crop production methods that can substitute methyl bromide to a large degree in many situations (Anon., 1993a, 1993b).

4.1.5.1 Non-chemical methods.

These include methods for treating soil that do not rely on the use of pesticides to suppress plant pathogens, phytonematodes, arthropods, or weeds; and methods of culturing plants in non-soil substrates. Among these are: the use of organic amendments, biological control agents, various cultural practices, plant breeding, grafting, and physical methods.

4.1.5.1.1 Organic amendments. The addition of organic matter to soil to improve fertility and manage pests and diseases is a practice almost as old as agriculture. A wide variety of materials has been tested as amendments to soil to manage nematodes, soilborne phytopathogenic fungi, and weeds. These include livestock manures, waste products from paper and forest industries (e.g. newsprint, paper mill digests, wood, etc.), oil cakes and pomaces, materials from seafood and fisheries operations (e.g. shells from shrimp and other crustaceans), sewage and other municipal wastes, as well as numerous by-products from agricultural, food and other industries, and allelopathic residues from plants (Hoitink, 1988; Mian, 1982; Rodríguez-Kábana, 1986; Rodríguez-Kábana *et al.*, 1987; Stirling, 1991). The efficacy of organic amendments against nematodes and other soilborne pathogens is dependent on chemical composition and physical properties which determine the type of microorganisms involved in their decomposition in soil. High nitrogen materials which generate nematicidal ammonia in soil, e.g. urea and guanidines, have been studied as amendments to soil for the management of nematodes and other plant pathogens (Canullo, 1991; Canullo *et al.*, 1992; Chian, 1990). The addition of chitin or chitinous materials to soil not only generates ammonia but also results in stimulation of the activities of chitinolytic microflora in soil (Culbreath, 1985; Godoy *et al.*, 1983; Rodríguez-Kábana *et al.*,1983, 1989, 1990). Many chitinolytic microorganisms are effective in the destruction of nematode eggs and mycelia of some phytopathogenic fungi. There is a large body of knowledge on the use of organic amendments for the management of soilborne pathogens (Cook and Baker, 1983; Hoitink, 1988). The possibilities for development of treatments to suppress phytonematodes and other soilborne pathogens are as varied as the types of "waste" raw materials available to prepare the amendments (Rodríguez-Kábana and Milch, 1991). A number of commercial products are available but are limited in efficacy. Successful organic amendments generally require large amounts of materials to be added to soil (> 50 t ha^{-1}). Consequently, their use is localised, limited by the availability of raw material and transportation costs. Nevertheless, these treatments can contribute to management of soilborne pests particularly when combined with other alternatives. For example, combining organic amendments to soil with solarisation (solar heating of soil under clear plastic cover) has been studied and offers considerable potential to increase efficacy of the amendments against pathogens and reduce amounts of material needed per hectare (Ramírez-Villapuda and Munnecke, 1988; Gamliel and Stapleton, 1993).

Certain plants contain allelopathic toxins that when released to soil through leaching, or biodegradation after incorporation in soil, inhibit the growth of competing weeds and pathogens. These properties have led to use of allelopathic residues from some plants such as annual rye (*Secale cereale*), and certain *Brassica* spp. or used as intercrops in orchards and as rotational or intercrops in annual grains and vegetables to impede weed growth. This is an area of active research and implementation in a number of countries (Anon., 1991; Baukloh, 1976; Franco *et al.*, 1993; Schlang, 1985, 1989; Schmidt, 1983; Thurston *et al.*, 1994; van Wambeke *et al.*, 1988).

Some substrates, used mostly in floriculture, may have suppressive effects on soil pests. When hardwood bark, composted or not, is used, improved plant growth is generally observed, especially in potted plants. Suppressiveness and improved plant vigour in such bark substrates result from the physical characteristics of bark compost and higher levels of antagonistic microorganisms supported by these composts. Bark composts show good antagonistic activity against *Phytophthora* spp., *Pythium* spp., *Rhizoctonia solani* and several *formae speciales* of *Fusarium oxysporum*. Such composts can be directly used for potted crops or can be used as sources for microbial antagonists to induce suppressiveness in conducive substrates (Hoitink, 1988).

A major problem in the use of organic amendments is the variability in composition of materials used for preparation of the amendments (Stirling, 1991). Nitrogen content of poultry litter, for example, can vary greatly depending on storage conditions, humidity, temperature, etc. The standardisation of composition of amendments, i.e. quality control, is an area needing development of appropriate methodology. Some organic amendments have the potential to accumulate deleterious compounds and increase the inoculum level of some soil pathogens (Cook and Baker, 1983; Rodríguez-Kábana, 1986).

CONCLUSIONS. *Alternatives to methyl bromide are currently available for specific problems and more may be developed using organic amendments. The spectrum of activity of the amendments, formulations, and rates to be used will depend on raw materials available for preparation of the amendments. This approach to control of phytonematodes and other soilborne plant pathogens will be necessarily localised and dependent on reliable sources of raw material for conversion into useful formulations. With this method, success in one area on certain specific pathogens does not necessarily mean that the same solution will supply the same results to the same specific pathogens in another area. Amendments can also be formulated to provide essential plant nutrients to serve as fertilisers that stimulate activities of soil microflora antagonistic to nematodes and other plant pathogens.*

4.1.5.1.2 Biological control. Soilborne plant pests exist in soil in equilibrium with other components of the soil biota. There is a great deal of literature available describing many types and species of organisms antagonistic to plant pathogens (Belarmino *et al.*, 1994; Burges, 1981; Cook and Baker, 1983; Ferrera Cerrato and Quintero Lizaola, 1993; Gomes Carneiro and Belarmino, 1994; Hornby, 1988; Jairajpuri *et al.*, 1990; Mukerji and Garg, 1986;

Rodríguez-Kábana, 1991; Rodríguez-Kábana and Canullo, 1992a, 1992b; Stirling, 1991). Research on the possibility of utilising antagonists to control plant pathogens has been going on for more than a century. Most of these studies are phenomenological in nature, providing descriptions of organisms or cases where a given pathogen was "controlled" by an organism. There are also descriptions of numerous attempts at utilizing soil microorgnisms for control of soilborne plant pathogens. However, to date there have been very few successes. The number of commercially available products whose mode of action is based on the introduction of biocontrol agents into soil is limited to less than six. Innate to the utilisation of biocontrol agents is the specificity of their activity. A given antagonistic fungus or bacterium, for example, will serve to control only a pathogen or a reduced number of pathogens. The introduction and establishment of an organism in soil requires that the organism be placed in an "unoccupied ecological niche" or that it be added in colonised substrate in large amounts (t ha^{-1}) to overwhelm competing indigenous organisms.

Soils suppressive to several soilborne pathogens (i.e. several *formae speciales* of *F. oxysporum*, *R. solani*, *Pythium ultimum*, *Phytophthora* spp., *Thielaviopsis basicola*, etc.) have been described in different areas (Cook and Baker, 1983; Parker *et al.*, 1985; Rodríguez-Kábana and Calvet, 1994). Soilborne diseases do not occur or are less severe in such soils. Antagonists isolated from suppressive soils and responsible for suppressiveness can be successfully used to control soilborne pathogens. Some preparations of such antagonists are now registered. In the future, use of antagonistic *Fusarium* spp. and/or fluorescent Pseudomonads, active against several formae speciales of *F. oxysporum* (f.sp. *dianthi*, f.sp. *lycopersici*, f.sp. *cyclaminis*, f.sp. *melonis*, f.sp. *basilicum*) may permit control of Fusarium wilts and other diseases. Also, use of *Trichoderma* spp. as seed dressing or soil treatment may provide better opportunities for control of damping-off and root rots caused by *Phytophthora* spp., *Pythium* spp., and *R. solani* (Cole and Zvenyika, 1988). However, in the case of antagonists, the spectrum of activity is generally limited. Moreover, often their activity significantly varies in different soils and, more generally, under different environmental and cultural conditions.

Plant growth promoting rhizobacteria. Another approach to biological control is the utilisation of rhizobacteria, i.e., bacterial species that develop in and around the roots of plants (Keel *et al.*, 1990; Kloepper *et al.*, 1988). Many rhizobacteria are antagonistic to pathogens and more importantly, can colonise the roots and establish a "biological shield" to delay invasion of the roots by nematodes and other pathogens. This concept implies a broadening of the spectrum of activity, since presumably occupation of the roots by rhizobacteria could prevent attacks from several pathogens. Many rhizobacteria can be introduced into soil in seed coverings or coatings. Following seed germination the bacteria will develop with the seedling roots and offer protection to the plant at its most critical early growth stages. There are now several rhizobacteria products in the market that have been successfully tested under field conditions. A beneficial side-effect of treatments with rhizobacteria is the frequently observed stimulation of plant growth; the terms Plant Growth Promoting Rhizobacteria (PGPR) or Plant Health Promoting Rhizobacteria (PHPR) refer to this phenomenon (Suslow, 1982).

Mycorrhizae. With few exceptions, all plant roots in nature develop in close association with specialised fungi forming a complex, the mycorrhizae (Ferrera Cerrato and Quintero Lizaola, 1993; Mosse, 1973; Perrin, 1991). Some mycorrhizae grow only on the surface and outer layers (ectomycorrhizae); others penetrate deeper into the root (endomycorrhizae). The type of mycorrhizae formed depends on the species of plant and fungi. There is a certain degree of specialisation in these plant-fungus systems. Most conifers, for example, have typical ectomycorrhizae. These root-fungus associations are for the most part beneficial in that they result in root proliferation and consequent increase in nutrient adsorptive root surface. This permits the plant to survive and thrive in environments where nutrients are limiting or are difficult to extract. In soils where nutrients are not limited, mycorrhizae may adversely affect plant health. There is also evidence that plants with mycorrhizae are more resistant to some soilborne diseases (Calvet *et al.*, 1993; Chet, 1987). There are commercial products available to inoculate plants with mycorrhizae (Rodríguez-Kábana and Calvet, 1994; Vozzo, 1971). A great deal of research is going on now to determine how best to exploit the beneficial effects of mycorrhizae to protect plants. This is particularly important since soil disinfestation with methyl bromide and other "broad-spectrum agents" has often been reported to eliminate mycorrhizal fungi from soil or to retard development with detrimental effects on some crops growing in the disinfected soil (Rodríguez-Kábana and Curl, 1980; Schenck, 1982).

Endophytes. Most plant species have a variety of endophytic microorganisms that develop in them which may be beneficial or detrimental to the plant or animals feeding upon the plant (Cook and Baker, 1983). The use of non-pathogenic endophytes to control or prevent plant diseases is a recent development in biological control. The possibility exists of using seed treatment to introduce selected antagonistic endophytes into plants. Successful introduction of endophytic antagonists in crops could remove one of the main disadvantages of biocontrol agents - their dependency on specific environmental conditions. The plant offers a protected environment for the endophyte. This makes it possible to have the same organism in a plant in as wide environmental conditions as are suitable for the plant species. Field research with cucumbers has shown that endophyte-inoculated plants are resistant against a variety of plant pathogens and had higher yields than cucumber plants raised conventionally (Ryder *et al*., 1994). The mechanism(s) underlying the resistance of the endophyte-plant system against pathogens is not well understood. There is evidence that the endophyte in the plant triggers a broad spectrum defence response of the plant against pathogens.

CONCLUSIONS. *Biological control of soilborne pests has been developed for various cropping systems and in some cases have been in use for many years. However, the spectrum of efficacy is generally limited to one, or a small number of pests. It is in use in greenhouse culture in some countries, but the efficacy significantly varies under different cultural and environmental conditions. It is unlikely that adequate substitutions for methyl bromide in field applications will be developed solely from biological control methodologies in the near (< 5 years) future. Biological control of soilborne pests is a research field much under-financed. Research should be encouraged and supported to develop new biological control products and, most importantly, to provide a broader understanding of the general ecology of the soil microbiota. This knowledge is essential for development of these alternatives to methyl bromide. It must be stressed that, when available, most biocontrol agents, due to their narrow spectrum of activity, are only able to solve very specific problems.*

The use of beneficial endophytic microorganisms and mycorrhizae fungi to protect plants against pathogens could be a solution to the problems of environmental specificity and narrow spectrum of activity encountered with other biocontrol agents. Research on this approach to biological control is still very preliminary. It is not possible to determine at present when efficacious products may become commercially available. Some biological control agents are commercially available for specific pests and situations.

4.1.5.1.3 Cultural practices. Crop production systems have been designed to suppress soilborne pests (Bello *et al*., 1994; Johnson, 1982; Rodríguez-Kábana and Canullo, 1992b; Trivedi and Barker, 1986). The use of appropriate cropping systems has led to sustained agricultural production for centuries in many parts of the world. It can be stated that for many pest problems, a cropping system can be developed to manage the problem(s).

Among the many cultural practices within production systems that offer alternatives to methyl bromide for the management of soilborne pests are: crop rotations, planting time strategies, deep ploughing, flooding, fallow, cover crops, intercropping, green manures, fertilisation, and plant growth substrates.

Crop rotations. Crop rotations can be an effective method for suppressing damage by soilborne pests. The literature on the subject is extensive and there are several reviews available (Cook and Baker, 1983; Rodríguez-Kábana and Canullo, 1992a, 1992b). Very effective rotations of non-host plants with agronomic and horticultural crops have been described for control of soilborne pests in many parts of the world.

It is possible to increase the suppressiveness of crop rotations on pathogens by including in cropping systems plants that are antagonistic to pathogens. Oilseed rape, for example, produces methyl isothiocyanate and related mustard oils which are fungicidal and nematicidal; these plants have been used in rotations to control several soilborne phytopathogenic fungi, cyst and root-knot nematodes in sugarbeet, potatoes, and other crops (Anon., 1991; Baukloh, 1976; Schlang, 1985, 1989; Schmidt, 1983). Crop rotation systems that include forage or pasture crops can also be very effective and profitable in that they introduce livestock production into the rotation system. The inclusion of disease resistant (or tolerant) cultivars, when available, within cropping systems can be a very effective way of managing pest problems without use of methyl bromide (Rodríguez-Kábana and Canullo, 1992b; Weaver and Rodríguez-Kábana, 1992). Limitations to this alternative are availability of land, persistent pest inoculum, appropriate rotational crops, equipment, expertise , and socio-economical considerations.

Planting time. Knowledge of population dynamics of plant pathogens sometimes suggests development of cultivars for planting in time intervals when pathogen inoculum is low and/or environmental conditions are not conducive to disease development. The efficacy of this approach was demonstrated in Georgia, U.S.A., where damage from root-knot nematodes was maintained at low levels through a combination of crop rotation and early planting to avoid periods optimal for nematode development (Heald, 1987; Johnson, 1982; Trivedi and Barker, 1986). Use of this technique may be limited in crops with inflexible marketing and production windows.

Deep ploughing can reduce pathogen inoculum through burial of reproductive structures and stimulation of microbial activity by decomposition of crop debris. Numbers of sclerotia of *Sclerotium rolfsii* in soil can be reduced significantly by deep burial - this operation has long been practiced in the production of peanut (*Arachis hypogaea*) and other crops in the southern U.S.A. to reduce the incidence of southern blight (Punja, 1985).

Flooding and water management. Where water is abundant and available, water management can have beneficial effects in the reduction of nematodes and other pests (Hollis and Rodríguez-Kábana, 1966; Rodríguez-Kábana and Hollis, 1965; Muller *et al.*, 1992; Muller and van Aartrijk, 1992). Flooding was effective in the control of Verticillium wilt of cotton (Cook and Baker, 1983; Pullman and DeVay, 1981) but was only partially useful for the management of Panama disease of bananas (*F. oxysporum* f. sp. *cubensis*) (Stover, 1962). It is particularly effective when organic matter is incorporated into soil prior to flooding. Anaerobic microbial activity can result in the production of metabolites toxic to many soilborne pests (Cook and Baker, 1983).

Fallowing. The practice of fallowing (taking land out of production) can be useful in reducing the impact of certain plant pests through denial of host and/or substrate for growth (Cook and Baker, 1983; Johnson, 1982; Trivedi and Barker, 1986). This practice may not be particularly reliable as many pathogens can survive prolonged fallow periods (e.g. *Verticillium* 15+ years, *Olpidium* 30+ years). There are numerous production systems throughout the world that include fallowing as part of a pest management program. Successful fallowing must avoid weeds that may serve as hosts or reservoirs for pathogens. It is for this reason that weed control, by herbicides or repeated cultivations, must be achieved. It is a common technique in many parts of the world, but its use is limited in areas with high land values, shortages of agricultural land or when pests can survive prolonged fallow periods.

Cover crops. Cover cropping is a very common practice consisting of planting a non-commercial crop which at a given level of maturity is turned back into the soil as green or dry residues. For example in Florida, winter vegetable production may be preceded by summer cover cropping with sorghum (*Sorghum bicolor*), sudan grass (*Sorghum* sp.), American jointvetch (*Aeschynomene americana*) or hairy indigo (*Indigofera hirsuta*). This practice has been beneficial in reducing damage from phytonematodes and other soilborne pathogens in the following winter vegetable crops (McSorley *et al.*, 1994; Rhoades, 1983). Cover crops must be designed into the cropping system so that they do not compete with the commercial crop.

A living mulch is a cover crop that is grown simultaneously with the main crop in a reduced tillage system. Living mulches can suppress weeds and reduce insect pests without reducing yields (Thurston *et al.*, 1994). Soil-dwelling and foliar insect numbers can also be kept below injury levels by the mulch. This may be due to confusing or repelling pest insects because of changes in reflected light produced by the mulch; attraction of natural enemies to the mulch which serves as habitat and alternative food source; loss of crop visibility to insects due to loss of contrast between bare soil and crop plant.

Fertilisation and plant nutrition. It is generally recognised that the maintenance of an adequate and balanced plant nutrition may reduce the impact of soilborne pests. The type of fertilisation used can affect pathogen and disease development. Phytonematodes, for example, are sometimes adversely affected by the use of urea or ammoniacal nitrogen sources (Franco *et al.*, 1993). As was discussed under organic amendments, this is directly related to microbial activity in soils. Ammoniacal nitrogen sources (e.g. ammonia, ammonium carbonate and ammonium bicarbonate) can reduce damage from *S. rolfsii* in carrots and other crops (Punja, 1985). Enhanced calcium nutrition through application of lime (calcium carbonate), or landplaster (calcium sulfate) can reduce pod rot (*Pythium myriotylum*, *Rhizoctonia solani*, *Fusarium* spp.) in peanut (Pattee and Young, 1982). In some cases, only a change in pH is required to cause reductions in some soil pests (Cook and Baker, 1983). These examples serve to demonstrate that a great deal can be done to reduce disease through appropriate management of fertilisers, nutrition, and soil pH.

Plant growth substrates. Artificial plant growth substrates allow culturing without soil fumigation. Substrates such as rock wool, tuff stone, clay granules, and flexible polyurethane foam blocks allow the plant root to absorb nutrients and water (Anon., 1992). Specialised farming systems with these substrates have demonstrated the technical and economic feasibility of totally eliminating use of methyl bromide in greenhouses and raised beds and, under good climatic circumstances, in open field (Anon., 1992). However, these specialised systems require adequately trained personnel. Substrates need to be disinfected between crops to avoid build-up of pathogen populations (Gamliel *et al.*, 1989; Sneh *et al.*, 1983). The disposal of certain substrates may involve environmental problems. However, some of these materials can be recycled or used to improve soil structure (Anon., 1992; Rockwool/Grodan, 1994). In most cases, the investments necessary for the substrate technique restrict its use to high value crops that are treated with methyl bromide.

In areas where volcanic pumice is available, production systems have been developed based on the heat absorbance and retention properties of the pumice. Pumices are utilised to heat the underlying soil and eliminate plant pathogens (Bello *et al.*, 1991, 1993).

CONCLUSION. *Cultural practices such as crop rotation, fallowing, cover crops, deep plowing, and others can be used to augment production systems suppressive of some plant pests. Prerequisite for the utilisation of these practices is, first of all, availability of land (for crop rotation), and abundance of water (for flooding) and also a good understanding of pests' dynamics and the general ecology in specific production fields. It is possible to develop pest-suppressive cropping systems within specific localities and reduce or eliminate use of methyl bromide. Information necessary for development and implementation of these systems is not available for most areas but may be obtained within five years or more. A major consideration with the crop rotation approach is that farmers may be forced to rely upon relatively few profitable crops (or even a single crop) with which they have experience rather than on a variety of crops, a prerequisite for development of effective crop rotations. The use of plant growth substrates has demonstrated the technical and economic feasibility of totally eliminating the use of methyl bromide in greenhouses in The Netherlands. This technology may be feasible in similar situations in other countries.*

4.1.5.1.4 Plant breeding and grafting. The selection and development of crop cultivars resistant or tolerant to pests is as old as agriculture. Systematic, scientific plant breeding, begun almost a century ago, has yielded crop cultivars resistant to many soilborne pests. There are, for most crop species today, varieties resistant (or tolerant) to root-knot nematodes or to phytopathogenic fungi in genera such as *Phytophthora*, *Fusarium*, *Verticillium*, and *Sclerotinia*. New resistant varieties to individual pests can be developed for some crops at a rate of one every 5-15 years depending on crop species and existing research commitment. Recent discovery that certain genes are turned on by root-knot nematodes (*Meloidogyne* spp.) offers hope for expediting development of resistant plant material (Opperman *et al*., 1994). There are however, limitations to what can be done through plant breeding even with up-to-date molecular techniques. It is very difficult to develop cultivars resistant to several pathogens. Most fields are infested with a multiplicity of major and minor plant pathogens. Frequently, the planting of a cultivar resistant to only a limited number of pathogens results in increased severity of disease caused by pathogens to which the cultivar is susceptible. Even for a single pathogen, cultivars may be resistant to a narrow spectrum of races within the pathogen's genome. This again can result in the appearance of "new races" through selection by the use of resistant cultivars. Resistant cultivars may not have desirable agronomic and marketable characteristics. Also, the instability of resistance genes in unfavourable environmental conditions, e.g. high soil temperature, may limit the efficacy of resistant plants (Trudgill, 1991). It is, however, possible to utilise resistant cultivars judiciously within a cropping system (Weaver and Rodríguez-Kábana, 1992). For example, alternate plantings of resistant and susceptible soybean cultivars have been used to prevent "race shifts" in fields infested with the cyst nematode, *Heterodera glycines* (Riggs and Wrather, 1992). Resistant cultivars can be integrated within crop rotation systems to enhance pathogen suppression by the systems (Cook and Baker, 1983; Trivedi and Barker, 1986).

Grafting of susceptible plants onto pathogen-resistant rootstock is an old method used in the production of fruit and nuts. More recently, efficient grafting techniques have been developed for annual crops, e.g. cucurbits, tomato, eggplants, to permit production of these crops without the need for fumigation. Tomato can be grafted onto *Solanum torvum* rootstock to obviate damage from root-knot nematodes and bacterial wilt (*Pseudomonas* spp.). Similarly, melons or cucumbers can be grafted onto wild melon or pumpkin rootstock to avoid problems caused by Fusarium wilt pathogens (Gómez, 1993). Grafting may permit quick response to market demands.

CONCLUSIONS. *Cultivars resistant or tolerant to single or limited number of specific pathogens (and races) are available for many crop species. In most cases new cultivars can be developed through plant breeding techniques to address specific pest problems. Plant breeding should be viewed as a permanent component of crop production but it is currently very difficult to develop cultivars resistant to several pathogens. Frequently the planting of a cultivar resistant to a limited number of pests results in increased damage from pests to which it is susceptible. Grafting of susceptible annual or perennial crops on resistant rootstocks is possible for some crop species. In some cases, grafting techniques can economically and efficiently permit production without the need for soil fumigation.*

4.1.5.1.5 Physical methods. Physical control of soilborne pests include such techniques as steam, solarisation, and wavelength-selective plastics. The only practical methods for sterilisation of soil are those based on the use of heat. Dry heat and steam treatments have been used for more than a century to treat soils.

Steam. Under the appropriate conditions, soil pasteurisation with steam at temperatures of 70 - 80°C is as effective as methyl bromide (Anon., 1992; Runia, 1983). Soil pasteurisation is aimed at reducing pathogen inoculum while retaining a significant portion of the soil microflora as a "biological shield" against re-infestation by undesirable microorganisms. Sterilisation of soil (>80°C) can result in a "biological vacuum" where any microorganism, including pathogens, can re-colonize the sterilised soil. In addition, prolonged treatment of soils at high temperatures (80 - 120°C) can result in destruction of soil structure and release of phytotoxic materials from soil organic matter. There is also evidence that heavy metals, e.g. manganese, are released by high temperature treatments with ensuing phytotoxic effects. There are however, methods available to use steam efficaciously with no phytotoxic after-effects. Steaming with or without negative pressure has replaced soil fumigation with methyl bromide in The Netherlands (Anon., 1992; Runia, 1983). At present, these steaming processes are used mostly in greenhouse operations in several countries.

Solarisation is of relatively recent development (Katan and DeVay, 1991) and consists of the treatment of soil with solar heat by covering the soil surface with thin, transparent plastic (mostly polyethylene) sheets for prolonged periods (Grinstein and Hetzroni, 1991). It is a form of pasteurisation in that it does not result in the sterilisation of soil. Solarisation was shown to be successful for management of many soilborne pathogens and other pests. Pest inoculum, including resting structures, in moist soil covered with plastic for four or more weeks can be significantly reduced or eliminated. This results not only in reduced disease incidence in the subsequent crops but also in significant yield increases. The mode of action of solarisation treatments is still under study. Increased soil temperature is essential for reducing soil inoculum but there are other important effects derived from microbial activity. There is good evidence for stimulation of beneficial microorganisms by solarisation in addition to thermal killing. Solarisation is most successful in dry climates with low number of cloudy days and intense solar heat. It is used by farmers in Greece, Israel, Italy, Spain and other places with similar Mediterranean type climates. Its value in areas of high rainfall, significant cloudiness, or wide fluctuations in daily temperatures is questionable (Grinstein and Hetzroni, 1991). Solarisation can be used in cooler climates by using closed plastic houses or greenhouses. This technique has been developed in northern Italy and it is used in Japan in over 2200 hectares of strawberry, eggplant, tomato, and cucumber (Horiuchi, 1991; Katan and DeVay, 1991). Solarisation may require treatment periods of 4 - 8 weeks, so that it may not be useful where such prolonged periods without crops are not available. The possibility of using solarisation while the crops are still in the ground has been demonstrated in almond, olive and pistachio groves and on cherry tomatoes. Solarisation has had mixed results in controlling phytonematodes. While it is effective for control of some ectoparastic and migratory endoparasites (*Ditylenchus* spp., *Pratylenchus* spp.) results obtained with endoparasitic root-knot nematodes (*Meloidogyne* spp.) have, in most cases, not been satisfactory (Heald, 1987). Soil solarisation does not effectively control certain weeds (e.g., nutsedge [*Cyperus* spp.]) and some deeply located fungal pathogens in the soil such as *Armillaria* spp. A serious problem in solarisation technology as with methyl bromide application, is the disposal of polyethylene sheets after treatment. Although a great deal of effort has been devoted to the recycling of these plastics, the problem is serious in some areas.

The combination of solarisation with other alternatives such as organic amendments and pesticides applied at reduced dosages has been successful for controlling nematodes and other soilborne pests (Afek *et al.*, 1991; Ben-Yephet *et al.*, 1988; Gamliel and Stapleton, 1993). These combination treatments may: 1) shorten the time needed for solarisation, 2) increase the efficacy and consistency of solarisation against pathogens and broaden its spectrum of activity to include phytonematodes, and 3) allow its use in cooler conditions.

Wavelength-selective plastic mulch. Wavelength-selective plastic mulches are used to heat the soil but prevent weed growth by excluding photosynthesising light waves from reaching the soil ('Hyplast', Hoogstraten, Belgium). They are also used in vegetable and berry production to prevent damage from various root maggots by serving as a barrier to adult insects that lay eggs at the base of host plants, or larvae that drop to the soil to complete their lifecycle.

Flaming/superheated water. The use of heat is one of the oldest weed control methods known to agriculture. While primitive agriculturists used fire, contemporary growers use heat technology in the form of hand-held or tractor-driven "flamers" or superheated water sprayers fuelled by propane or other petroleum products. These implements are used to control weeds in orchards, cotton, vegetables, and many other crops. Large and small-scale commercial flaming equipment is available in most countries. The technology for superheated water application is a recent development and commercially available in New Zealand and the U.S.A. In many cases, thermal manipulations of habitat via hot water dips have also been successfully used within regulatory plant certification programs to control nematodes in infested plant material (Heald, 1987).

Low temperatures to suppress nematodes. Thermophilous species of nematodes are susceptible to low temperatures. In greenhouse systems, soil temperatures below 20°C can be used for the management of some species of root-knot nematodes. The utility of using low temperatures to control phytopathogenic nematode species merits research attention (Bello, 1994; Fernández *et al.*, 1993).

Irradiation and microwave technologies for treatment of soils. Other physical methods, based on the use of irradiation microwaves and radio frequency heating, may have potential for managing particularly specific pests in specific systems. Irradiation technologies pertain particularly to the treatment of containerized or potting soils as well as nursery pots, mats and other reusable items, but not to broad acre applications. The commercial irradiation of nursery pots, seedling containers and mats for disinfestation and disinfection have assisted the glasshouse industry in Netherlands to discontinue use of methyl bromide; the recycling of these containers has resulted in less solid waste generated for landfills. While some research has been conducted on the irradiation of potting soils, further research on this is required to determine the potential of this alternative.

Numerous laboratory studies have indicated the potential for heat treatments applied with microwaves and radio frequency radiation in pest disinfestation of growing substrates and soils. Although there may be a potential for treating small quantities of substrate (e.g., bagged potting soil), more information is required on the feasibility of this approach on a larger scale (van Wambeke, 1987; van Wambeke *et al.*, 1983,1984; Vela *et al.*, 1976).

***CONCLUSION.** Under the appropriate conditions, soil pasteurisation with steam is as effective as methyl bromide. New technologies for application of steam to soil under negative pressure replaced soil fumigation with methyl bromide in greenhouse cultures in The Netherlands and this technology may be applicable in some other countries. Soil solarisation may offer an alternative to methyl bromide in areas with long periods of low cloudiness and intense solar heating. Solarisation is now used by producers in many parts of the world either alone, or more often in combination with another agent such as organic amendments or low dosages of pesticides. Also solarisation methods may be improved to extend the value of these treatments into other areas with more research and development. Wavelength-selective plastic mulches, superheated water, low temperatures, and microwave technologies may also have some usefulness with more research. A disadvantage of methods which requires the burning of fossil fuels for the production of heat is their potential impact on global warming (but see Section 3.3).*

4.1.5.1.6 Research priorities for non-chemical alternatives

Short term (five years or less)

1. Incorporate existing knowledge and methods of non-chemical controls into crop production systems as an alternative to the use of methyl bromide.

2. Develop effective methods of transferring existing knowledge and experiences on alternatives between different regions and countries.

Long term (more than five years)

1. Long term basic research is necessary to develop an understanding of soil ecology as it relates to the etiology, pathogenicity, epidemiology and suppression of arthropod pests, nematodes, diseases and weeds in the development of crop management systems. Research results should be continuously integrated into crop management systems.

- Investigate effects of cultural control methods such as organic soil amendments and crop rotation on pathogen and soilborne biotic populations in relation to crop production. Methods for production of amendments and application techniques need to be developed to reduce inconsistency or variability in degree of pest control obtained with amendments to soil.

- Investigate factors related to root protection by root-influencing organisms such as rhizobacteria, mycorrhizae, and endophytic microorganisms. Methods need to be developed which enhance root protection organisms in a variety of soil types.

- Determine efficacy of potential biological control organisms and methods of use.

2. Evaluate and develop germplasm and cultivars for resistance or tolerance to major soilborne pathogens for major crops affected by loss of methyl bromide.

4.1.5.2 Chemical methods

Chemical compounds that can be considered as alternatives for methyl bromide may be classified according to their availability to the market. There are compounds that are currently available in agriculture; others will require additional research and registration before they can be utilised by producers (Martin and Woodcock, 1983; Thomson, 1989). One of the considerations in evaluating chemical alternatives is the fact that methyl bromide is an effective viricide, a property that is lacking or has not been reported for other chemical alternatives.

The relative toxicity and safety of chemical alternatives to methyl bromide is an important consideration. Annex 4.1.3 presents a sample summary of relevant toxicological information available for chemical alternatives considered in this report. Additional information is presented for some of the chemicals in the text. Classification of acute toxicity is based on OECD (Organization for Economic Cooperation and Development) guidelines and carcinogenicity according to IARC (International Agency for Research on Cancer) guidelines.

4.1.5.2.1 Fumigants. A fumigant is a chemical which, under typical field conditions, exists as a gas or is converted into a gas, in sufficient concentration to be lethal to pest organisms. Distribution of fumigants through soil is principally in the gas or vapour phase. Fumigants typically can be expected to show biological activity at a place remote from the point of application. By contrast, a non-fumigant is a chemical that is toxic to pests as a solid or liquid. Their movement through soil is usually by solution in water or other mechanisms not involving a gas or vapour phase.

Methyl isothiocyanate (MITC). This compound has been effective for the control of arthropods, some weeds and soilborne pathogens, principally fungi and a limited number of plant parasitic nematode species (Rodríguez-Kábana *et al.*, 1977). It is mostly used in combinations with 1,3-dichloropropene (1,3-D) which enhances the nematicidal activity. It is a liquid and is injected into the soil. Problems with product stability and corrosion have limited the use and distribution of this compound. The toxicological profile of MITC (toxic, skin and eye irritant, sensitiser) may be a technical constraint to its use as an alternative. MITC has the physical characteristics indicating its potential to contaminate ground water; however, monitoring has not revealed groundwater contamination.

MITC Generators. These are compounds or their formulations which, when incorporated into moist soil, decompose to produce methyl isothiocyanate. The spectrum of activity of MITC generators is similar to MITC (Rodríguez-Kábana *et al.*, 1977). These materials have been commercially available for 40 years. Inconsistent results have been reported with these materials because uniform distribution of formulated product and release of MITC in the soil are highly dependent upon application method, adequate soil moisture, temperature, pH, and the effectiveness of the soil surface sealing method (e.g. waterseal, covering with plastic or

Metam-sodium. Metam-sodium is formulated as a liquid and may be applied to the soil by either injection, drip or sprinkler irrigation, or sprayed on the soil surface prior to tilling. The toxicological profile of metam-sodium (mildly toxic, eye irritant, teratogen, genotoxin) may be a technical constraint to its use as an alternative.

Dazomet. Dazomet is formulated as a granule and is incorporated into the soil generally by roto-tilling (Anon., 1989). Although dazomet is a MITC generator, it produces other breakdown products such as carbon bisulphide and formaldehyde. Persistence in soil of MITC or breakdown products is influenced by temperature and moisture, which, if sub-optimal such as cool and wet, often require longer waiting periods before planting to prevent crop phytotoxicity. The main breakdown products of dazomet are MITC and formaldehyde.

Conclusions. *These compounds are immediately available and effective for control of certain pests, but successful treatment with them is strongly dependent on ideal application conditions. Phytotoxicity can be an important post-treatment effect.*

Halogenated hydrocarbons. 1,3-dichloropropene (1,3-D). This material is an effective nematicide but it has limited fungicidal and herbicidal activity (Johnson and Feldmesser, 1987; Rodríguez-Kábana *et al*., 1977). It is formulated as a liquid and injected into the soil followed by some method of soil sealing. The toxicological profile of 1,3-D (toxic, skin and eye irritant, sensitiser, genotoxin, suspected carcinogen) may be a technical constraint to its use as an alternative.

1,3-D has been found to contaminate groundwater only in areas of porous soils and high water tables.

Chloropicrin (trichloronitromethane). This material is highly effective for the control of soilborne pathogens and some arthropods (Wilhelm *et al*., 1974; Wilhelm and Westerlund, 1994). It is a weak nematicide and herbicide. Chloropicrin is a liquid and is injected into the soil followed by covering with plastic. In the absence of nematodes, improved growth and yield responses with chloropicrin are similar or superior to methyl bromide alone. It is known to enrich the soil with fungi and bacteria which are antagonistic to many plant pathogens. Chloropicrin alone diffuses well through the soil, but it is usually used in combination with methyl bromide at various percentages for the added control of weeds and nematodes (Wilhelm *et al*., 1974). The toxicological profile of chloropicrin (toxic, skin and eye irritant, sensitiser, teratogen, genotoxin) may be a technical constraint to its use as an alternative.

Ethylene dibromide (EDB). This material is an effective nematicide with activity against some arthropods (Johnson and Feldmesser, 1987; Rodríguez-Kábana *et al*., 1977). It is a liquid and is injected into the soil. The toxicological profile of EDB (toxic, skin and eye irritant, reproductive toxin, genotoxin, carcinogen) may be a technical constraint to its use as an alternative. Its use was banned in some countries because of groundwater contamination and carcinogenic effects.

CONCLUSIONS. *Halogenated hydrocarbons can be applied with few modifications using the same equipment that is used for methyl bromide. However, because the vapor pressure of these materials is less than that of methyl bromide, their movement in soil is more limited. These compounds have been used successfully for the production of crops under the same cultural conditions in which methyl bromide is now used (Overman and Jones, 1984). For pests on which halogenated hydrocarbons are effective, their performance is relatively consistent. Aeration and dissipation from soil following fumigation with these compounds is slower than with methyl bromide, requiring longer waiting periods before planting.*

Mixtures of fumigants. Mixtures of soil fumigants may provide a spectrum of soil pest control approaching that of methyl bromide (Overman and Jones, 1984). For example, Vorlex

(Rodríguez-Kábana *et al.*, 1977; Thomson, 1989). Included are crops in the same areas where methyl bromide is used. These combination products may represent the most efficacious short term alternatives to methyl bromide. Other combination products, such as EDB plus MITC or chloropicrin have also been used for many years. Preformulated mixtures must be tested and registered. The use of non-preformulated combination treatments may raise health and environmental concerns.

4.1.5.2.2 Non-fumigants. Control of weeds, insects, nematodes, and soilborne pathogens approximating the control found with methyl bromide may be achieved in some cases through the use of combinations of available non-fumigant materials (such as herbicides, fungicides, nematicides and insecticides). These chemicals may also be combined with other fumigants or non-chemical approaches. Some of these combinations are used commercially and are effective in many production systems. However, the full spectrum of activity for most of these combinations is not well understood and requires additional research. A comprehensive listing and description of these non-fumigant chemical alternatives, and their possible combinations, is available in crop protection manuals (Thomson, 1989). All non-fumigant nematicides are organophosphates or carbamates and therefore are highly acutely toxic neurotoxins (cholinesterase inhibitors) (Johnson and Feldmesser, 1987). Several non-fumigant pesticides have been detected in groundwater under certain conditions, and have health and safety limitations.

AVAILABLE CHEMICALS - CONCLUSIONS

None of the available chemical alternatives alone offer the broad spectrum disinfestation attributes of methyl bromide. It may be possible to achieve similar results from combinations of fumigants, non-fumigants, and non-chemical alternatives. Further research on application techniques, in some cases, may enhance the activity of various alternative fumigants. Non-fumigant alternatives are especially problematic due to the ability of many soil pests to develop resistance or the potential of soil microflora to decompose these chemicals. In addition, environmental and health considerations may limit the use of any pesticide.

4.1.5.2.3 Chemical alternatives which require further development

Formaldehyde. Formaldehyde may be applied as a liquid solution or can be generated in soil after application of granular paraformaldehyde (Rodríguez-Kábana *et al.*, 1977; Johnson and Feldmesser, 1987; Thomson, 1989). It does not require covering with plastic but water sealing or equivalent is necessary. This compound is primarily a bactericide with limited activity against ectoparasitic nematodes and some fungi. Early use of this material was limited because of phytotoxicity problems. Recently, new formulations with reduced phytotoxicity have been developed which may offer possibilities as a soil fumigant. The waiting period following treatment is highly temperature dependent. No information is available regarding its potential to contaminate groundwater. The toxicological profile of formaldehyde (toxic, skin and eye irritant, reproductive toxin, genotoxin, carcinogen) may be a technical constraint to its use as an alternative.

Carbon bisulphide (CS_2). CS_2 is a liquid that is injected into soil. No covering is required. It was formerly used for its insecticidal properties but it has limited fungicidal and nematicidal activity (Rodríguez-Kábana *et al.*, 1977; Thomson, 1989). Also, because of phytotoxicity, carbon bisulphide, like formaldehyde, may require long (> 2 weeks) waiting periods before soil can be planted. It is flammable and explosive. The toxicological profile of carbon bisulphide (harmful, skin and eye irritant, reproductive toxin, teratogen, carcinogen) may be a technical constraint to its use as an alternative.

Sodium tetrathiocarbonate is a water soluble salt formulated in stabilised concentrated aqueous solutions which can be applied to soil. Decomposition of this material releases CS_2

These materials do not show much promise as adequate alternatives to methyl bromide at this time.

Dichloro-isopropyl ether. This compound is available in liquid and granular formulations (Thomson, 1989). It is marketed in Japan for nematode control in fruits, vegetables and tobacco, but it has shown variable activity in other countries. The toxicological profile of dichloro-isopropyl ether (toxic, skin and eye irritant, suspected carcinogen) may be a technical constraint to its use as an alternative.

Anhydrous ammonia (NH_3). Anhydrous ammonia is a gas at standard atmospheric pressure. It is sold in pressurised containers for use as a fertiliser. Ammonia is injected into the soil and no covering is necessary. It has a broad spectrum of activity against soilborne pests (Punja, 1985; Rodríguez-Kábana *et al*., 1981, 1982). Its high solubility in water (pH dependent) and retention in clay and soil organic matter impede its diffusion and movement through soil. This may account for the variable results obtained when used against soilborne pests. Ammonia is inexpensive and methodology may be developed to make its use practical.

The toxicological profile of anhydrous ammonia (toxic, skin and eye irritant) may be a technical constraint to its use as an alternative.

Sulphur dioxide (SO_2). SO_2 is a gas that has been considered for soil treatment of plant pathogens; however, there is very little information on its efficacy or non-target effects in soil (Rodríguez-Kábana *et al*., 1977). Sulphur dioxide is inexpensive and methodology may be developed to make its use practical. The toxicological profile of sulphur dioxide (toxic, skin and eye irritant, reproductive toxin, genotoxin, suspected carcinogen) may be a technical constraint to its use as an alternative. It is an atmospheric pollutant and its concentration in the atmosphere is closely monitored in many countries.

Bromine-containing compounds. Propargyl bromide (- 3-bromo-1-propyne) was used as an additive to enhance the fungicidal properties of methyl bromide-chloropicrin mixtures for the control of soiborne pests and reduce the amount of methyl bromide and chloropicrin (Rhode, *et al*., 1980). Trizone, a combination of 30% chlroropicrin, 61% methyl bromide, and 9% propargyl bromide was manufactured by Dow Chemical but was discontinued in 1968. Propargyl bromide was formulated as a gel for application to soil without covering; however, it resulted in high bromide residues, a fact which contributed to discontinuation of its development as a soil fumigant (van Wambeke *et al*., 1986).

Bromonitromethane is a broad spectrum, very reactive fumigant. It is a liquid at standard pressure and temperature. The potential of this compound as a soil fumigant was recognised recently (Rodríguez-Kábana et. al., 1991). It is an irritant and lachrimatory material but no other data are available on its toxicity. The toxicological profile of propargyl bromide and bromonitromethane (skin and eye irritants) may be a technical constraint to their use as alternatives.

Inorganic azides - These materials are solids and can be formulated as granules or liquids. When added to soils they release hydrazoic acid (HN_3) which escapes to the atmosphere or is converted to nitrate in soil. Azides applied to soil demonstrated broad spectrum activity against weeds and soilborne phytopathogenic fungi, but higher rates are required for nematode control (Kelley and Rodríguez-Kábana, 1979a; Rodríguez-Kábana *et al*., 1972; van Wambeke *et al*., 1984, 1985; van Wambeke and van den Abeele, 1983). Application rate reductions are possible with covering. Microbiological studies of soil treated with NaN_3 for several years indicated enrichment of treated soils with a group of fungi antagonistic to many soilborne phytopathogenic fungi (Kelley and Rodríguez-Kábana, 1975, 1979b, 1981). A serious limitation to the use of NaN_3 or KN_3 is the possibility of formation of explosive azides when

Others - Research on the nematicidal and microbiocidal properties of some volatile, naturally occurring compounds has shown promise for development of new soil treatments for the management of nematodes and other soilborne plant pathogens (Soler-Serratosa, 1993). Furfuraldehyde, for example, has been shown to be effective for the management of nematodes and some phytopathogenic fungi (Rodríguez-Kábana *et al.*, 1993; Rodríguez-Kábana and Walters, 1992). Addition of this volatile material to soil enhances populations of fungi and bacteria that are known antagonists of many plant pathogens.

CONCLUSION

Some of the materials listed as "requiring further research" were previously used with varying degrees of success, but interest in the research and use of these declined after the introduction of new technologies, including methyl bromide. Renewed interest and research using more sophisticated application equipment and formulation techniques may lead to re-establishment of these pesticides as viable tools. Additional research on toxicology, ecotoxicity and residues will be needed for regulatory purposes for some of these pesticides.

4.1.5.2.4 Research priorities for chemical alternatives

Short term (5 years or less)

1. Evaluate the effects of individual chemical alternatives on pest control, yield, quality, environmental, health and safety impacts and cost-benefit ratios.

2. Evaluate combinations of chemical alternatives for soil treatment (e.g. 1,3-dichloropropene + chloropicrin or 1,3-dichloropropene + MITC).

3. Evaluate combinations of chemicals with non-chemical alternatives (e.g. soil fumigants + solarisation).

4. Evaluate use parameters for chemical alternatives that are consistent with IPM strategies and methodologies.

5. Improve application equipment and chemical use patterns.

Long term (more than 5 years)

1. Screening of naturally occurring and synthesised chemicals for activity against soil pests.

4.1.6 Emission reduction

The inclusion of methyl bromide in the Montreal Protocol is due to its emissions to the atmosphere and consequent effect on the ozone layer. Implementation of existing technology and research and development of new technology may significantly reduce emissions while maintaining the efficacy of methyl bromide.

4.1.6.1 Reduced dosage

In current practice, dosages of methyl bromide applied to treated fields are often higher than needed for control. This practice is considered necessary to compensate for the wide range of conditions under which fumigations occur (e.g. variations in pest susceptibility, soil type, moisture, temperature, land preparation, and application techniques). Although some information is available on the minimum dosage needed for pest control under various combinations of these conditions, more data are needed to reduce dosage and consequently

1976; Munnecke and van Gundy, 1979). The first step in this process is to generate laboratory and field data on the time required for acceptable control of specific soilborne pests under a given temperature and concentration (Munnecke and Lindgren, 1954). If temperature is held constant then, within certain limits, the time required for control is inversely related to concentration. If the concentration is doubled then exposure time is cut by half. This can be expressed as a *ct*-product. These *ct* values can be used to determine the minimum dosage of methyl bromide for field applications at a given field temperature. It is necessary in all cases to confirm with actual field study the predictions made with *ct*-based models.

4.1.6.2 Plastic soil covers

There are many types of plastic films used in the soil fumigation process (Bakker, 1993; de Heer *et al.*, 1983; Hamaker, 1983). The barrier properties of these plastic films can vary considerably based on plastic composition, windspeed, temperature, and film thickness (Basile *et al.*, 1986; De Heer *et al.*, 1983; van Wambeke, 1989b). For example, high density polyethylene films tend to provide a greater barrier to methyl bromide than low density polyethylene (LDPE) films. Also for monolayer films, there is a direct correlation between film thickness and permeability to methyl bromide, as film thickness increases, so permeability decreases. A number of new covers are available that are significantly less permeable to methyl bromide than LDPE (van Wambeke, 1983, 1989a, 1989b). Generally these films are more expensive and can be more difficult to handle in the field (Bakker, 1993).

Under suitable climatic conditions (no air movement, low temperature) high barrier films offer the advantages of permitting a significant reduction in dosage while maintaining the *ct* values needed for effective control. This is possible because less methyl bromide is lost to the atmosphere while the plastic cover is in place. The right combination of reduced dosage along with longer fumigation periods will also result in effective *ct* values. Longer covering has the additional advantage of allowing for opportunities for greater degradation of methyl bromide in the soil profile and thus further reducing the amount emitted to the atmosphere. Degradation is due to reaction with soil organic matter and some mineral constituents as well as other reaction pathways such as hydrolysis (De Heer *et al.*, 1983). Additionally emissions can be reduced by taking more care in sealing edges, sealing overlaps and by repairing mechanical damage to the cover. Following these measures, it is anticipated that emission reductions of 30% or higher can be attained. In cases where the application is not purely mechanical, the success of using new plastics greatly depends on the skill of the operator and the degree of quality control exercised.

4.1.6.3 Improving application techniques

Traditionally methyl bromide has been applied to soil by direct injection or by surface application under plastic covers (Rodríguez-Kábana *et al.*, 1977). Better application systems need to be developed which will result in a more uniform distribution of the gas in the soil profile and reduce the loss of gas during the application process (Kolbezen *et al.*, 1974; McKenry and Thomason, 1976; Rhode *et al.*, 1980; van Wambeke, 1989a, 1989b, 1992). Two examples of processes which could accomplish this goal are systems which allow for deeper injection of the fumigant and systems which reduce the number of injection shanks. Both deeper injection and fewer shank tracks reduce the emission rate of fumigant from the soil surface, without compromising the dosage required for effective control.

4.1.6.4 Reducing leakage during greenhouse fumigation

Keeping ventilation in greenhouses as low as possible during the cover period is important for reducing emissions. From experiments it was concluded that air movement inside of the greenhouse as a result of ventilation (opening of windows and doors) is probably the most important factor influencing the leakage of methyl bromide from underneath the plastic covers (Bakker, 1993; de Heer *et al.*, 1983; van Wambeke *et al.*, 1986).

4.1.6.5 Use of diffusion enhancing co-fumigants

Reduced application rates can be used when using diffusion enhancing co-fumigants with methyl bromide under improved plastic covers (van Wambeke, 1983; van Wambeke *et al.*, 1986). These co-fumigants do not necessarily show pesticidal properties by themselves. The co-fumigant must have a gas density comparable to methyl bromide and it should be competitive in adsorption to soil particles. This results in a longer availability of effective methyl bromide concentrations but may result in less adsorption and decomposition of the chemical. Research in this area is in the preliminary stages.

4.1.6.6 Reduced frequency of application

Depending upon the crop/pest combination, the frequency of methyl bromide applications may be reduced or, if possible, the chemical may be used in rotation with alternative control measures. This approach will require additional information and research regarding the detection and economic thresholds of the various pests, when known, upon the crop(s) of interest.

4.1.6.7 Research priorities for reduced emissions

Short term (5 years or less)

1. Develop plastics with improved handling, barrier and disposal properties.
2. Quantify the relationship between *ct* values and efficacy.
3. Improve application methodologies.
4. Evaluate the efficacy of combining reduced methyl bromide application rates with other methods such as solarisation, cultural practices, and beneficial organisms.

Long term (more than 5 years)

1. Evaluate the efficacy of combining reduced methyl bromide application rates with other methods such as co-fumigants, beneficial organisms, and cultural practices.
2. Develop methodologies to reduce the frequency of applications.
3. Develop technologies for *in situ* de-activation of methyl bromide after fumigation.

4.1.7 Research priorities

The primary goal of the research agenda is to develop least-toxic alternative methods and cropping systems that are both cost-effective and environmentally sound in the long term. With this goal the following research priorities are recommended:

1. Identify current research on pre-plant soil fumigation and establish a comprehensive data and information base for all current and past research. Establish an international communication vehicle to distribute this information that ensures coordination of existing research efforts and expansion of necessary research.
2. Improve methodologies to monitor population dynamics of soilborne pests. Develop a more comprehensive understanding of microbial interactions and other ecological impacts

3. Improve methods of monitoring and defining economic thresholds that will enhance the development of a cultural systems approach based on IPM programs.

4. Develop methods to produce pest-free propagation materials inoculated with beneficial microorganisms to minimise the need for alternative treatment methods.

5. Evaluate existing and proposed chemical and non-chemical alternatives and the application technology required to maximise their utility and reduce emissions.

- The emphasis in the short term (2 - 5 years) should include studies on appropriate timing of application, determination of minimum efficacious rates, and the integration of existing alternatives into an IPM strategy. As much as possible, currently existing programs and expertise should be utilised and supported.

- The emphasis in the long term (5+ years) should include the development of cultural/crop systems, which maximise non-chemical control strategies and maximise the efficacy of the required crop protection chemicals.

6. Evaluate the modification of the soil environment by chemical fumigants, crop residues, and botanical extracts on the ecology and the resulting recolonisation of the soil by beneficial microorganisms.

7. Develop emission reduction with the development of plastics with improved handling, barrier and disposal properties, quantify the relationship between *ct*-values and efficacy, improve application methodologies, evaluate the efficacy of combining reduced methyl bromide application rates with other methods such as solarisation, cultural practices, and beneficial organisms; develop methodologies to reduce the frequency of applications.

4.1.8 Transfer of knowledge and training in improvements

Information and research on many of the non-chemical methods and chemical alternatives to methyl bromide for each cropping system is incomplete or non-existent. Additionally, the use of improved technology and application methods for reduced emissions from soil fumigation (i.e. the use of high barrier plastic covers, and reduced dosages) is the most expedient means for rapidly decreasing methyl bromide emissions to the atmosphere.

As new information on alternatives and emission reduction becomes available, systems to transfer this knowledge must be implemented. The most likely avenue would be through agricultural specialists representing government agencies and NGOs, UN organisations, institutes of higher education and product distributors. These individuals and organisations need to be equipped to inform the end users of appropriate alternative methods and improved application technologies through the use of publications, training seminars and field demonstrations. In some countries the infrastructure for transferring this information may not be well established.

4.1.9 Uses without known alternatives

The problems associated with soil fumigation with methyl bromide are so complex that this section, although applicable to other methyl bromide uses, is beyond the scope of this Sub-Committee. Often the situations for which there are no known replacements are localised because of marketing and/or environmental conditions; what is an irreplaceable use of methyl bromide in one area may not be the case in another.

4.1.10 Constraints

Since there is no single substitute for methyl bromide, multiple IPM strategies and tactics, used simultaneously are required. Each strategy or tactic may have constraints, but the package of approaches can be tailored to specific sites and situations and provide effective pest management under many conditions. In this context, constraints are viewed as indicating research gaps and should receive priority attention. Research to overcome constraints should focus not only on biophysical systems, but also on socio-economic parameters. Changes in socio-economic context can reduce constraints on technical options.

Other options for overcoming constraints include: (1) strong incentive programs (e.g., IPM transition insurance, cost-sharing on implementing IPM alternatives to methyl bromide, tax incentives, etc.); (2) accelerated technology transfer programs emphasising farmer-to-farmer communication, on-farm demonstrations, and technical support on alternatives.

4.1.10.1 Environmental

Crops grown in soils treated with methyl bromide are cultivated worldwide, from the tropics to the subfrigid zone, and in areas with high to low rainfall. In these same areas, production also occurs in greenhouses with dissimilar environmental conditions and pest complexes.

The diversity of production is probably the single most significant constraint to replacing methyl bromide. Certain alternatives are only effective in specific regions. For example, where water supplies are scarce, the use of flooding is not practicable. Soil solarisation is not effective in areas with high rainfall, significant cloudiness and fluctuation in daily temperature. Steaming has limitations when used in heavy soils where special techniques, e.g. use of negative pressure, are necessary to obtain satisfactory pest control.

An alternative strategy which can be effectively used in greenhouse or field in one region may not be transferable to another due to a change in environmental conditions (e.g., temperature, rainfall, humidity, soil type, topography, etc.). Additionally, the global incidence and severity of soilborne pests is determined by environmental conditions.

4.1.10.2 Logistical

Land availability is limited and land values are high in many of the areas of intense methyl bromide use. Thus, continuous production of one or a few relatively high value crops may be required to obtain adequate profitability. The use of cultural practices which remove land from production for extended periods of time (fallowing, cover crops, solarisation, flooding) may not be practical in these areas. In addition, alternative pest control strategies which require longer soil preparation times or extended preplanting intervals will be difficult to implement under these conditions.

Market considerations are critical in determining planting times for many crops utilising methyl bromide fumigation. Alternative pest control strategies that impact on planting time may not be applicable for these crops. For example, planting during times of low pest inoculum may result in crop maturity at a time when the returns on that crop are unprofitable.

Labour is an important component in the production of crops fumigated with methyl bromide and may be limited during periods of peak production activity such as planting and harvesting. Adequate labour may not be available to implement some alternative control practices. For example, increased labour may be required for alternatives based on combination treatments.

The adoption of alternative strategies will require the development and acquisition of specialised equipment and new patterns for the use of equipment.

4.1.10.3 Health, safety and environment

Agrochemicals are regulated by government agencies and are sold and used by special permits and other specific label requirements. On a global basis there is no uniformity in regulatory requirements which include toxicology, ecotoxicology, environmental fate, aquatic toxicity, residues and others. A constraint to the adoption of a chemical alternative is the possible absence of registration for many uses.

Many existing agrochemicals are under scrutiny for their ability to cause a wide array of potential health effects (e.g., reproductive toxicology, carcinogenicity and neurotoxicity). Additional studies are required for environmental issues like metabolism, residues, ground water and soil contamination and emissions to air. Annex 4.1.3 shows that some alternative chemicals to methyl bromide are listed as suspect carcinogens, mutagens, or reproductive toxins by international agencies e.g., the International Agency for Cancer Research (IARC).

It is very likely that regulatory restrictions on use of chemicals will increase, and chemical treatments against agricultural pests will be problematic and will involve additional time and expenditures.

A constraint to the use of some non-chemical alternatives may also involve health, regulatory or environmental concerns.

4.1.10.4 Biotic

Breeding cultivars resistant to soilborne pests is a keystone for pest management systems. However, the use of this approach has definite limitations. Most cultivars are resistant to an individual pest or a limited spectrum of pest species and races. Use of these cultivars may result in changes in community structure or genetic composition of pests. New pest species and races may appear in response to repeated use of individual resistant cultivars. For some crops, development of multi-pest resistant cultivars is currently not feasible. There is a lack of correlation between what can be achieved through breeding for resistance and the number of pests present in soils. For some pest complexes (e.g. fungi x nematodes x insects x viruses) there are no cultivars available resistant to the complex, even though there are cultivars resistant to individual pest components of the complex. Cultivars with a limited resistance spectrum can be used rationally as components of pest management systems. To use these cultivars, accurate information on the biology, dynamics, and general ecology of pests must be available which is not always the case. Alternation between resistant and susceptible cultivars can prevent many of the problems of species and race shifts arising from the use of resistant cultivars. Breeding for horizontal or field resistance (multi-gene based) should be encouraged when possible to overcome these problems. Currently most breeding programs are not oriented towards horizontal or field resistance.

Biological control agents are generally highly adapted to specific hosts, target organisms, and environments. Small variations in any of these parameters may reduce or eliminate efficacy.

4.1.10.5 Informational

It would appear that many new alternative strategies for soil pest control will need to be developed and successfully implemented on a broad scale commercial agricultural basis to replace the pest control and crop production attributes of methyl bromide (Anon., 1993a, 1993b). Some of these alternative approaches have not been intensively studied and additional research will be required to characterise and maximise pest specific efficacy, crop production consistency, and geographical transferability. Although many different alternative strategies are currently under study, most have not been developed to allow immediate transfer and adoption to growers, at least without inherent risks.

To overcome these informational voids or constraints, new information will need to become available. New multidisciplinary research and extension programs will therefore need to be developed to consider a diversity of crops, environments, production systems and pest complexes. New systems for information organisation and archives to ensure rapid retrieval and dissemination will also likely be required. New educational programs and special training seminars for crop care consultants, farm-employed pest managers and/or growers will have to be conducted to ensure and expedite information transfer. Finally, and most importantly, to provide this information, adequate funds, equipment, and personnel to support information and technology transfer activities will need to become available.

4.1.10.6 Economic

The primary consideration is to ensure that the alternative system enables the farmers to produce a crop which is profitable without additional risks.

For most cases, information necessary for risk assessment of the transition to alternative production systems is not available. For example, the effect of these alternative systems on such factors as availability of capital, and marketing opportunities are unknown, thus financing by the traditional agricultural funding sources is problematic.

4.1.10.7 Sociological/psychological

Reluctance to change is a common human trait. For many growers and others facing loss of methyl bromide, this trait is reinforced by fear of potential economic losses, lack of knowledge about or experience with alternatives, and lack of an extensive research base or technology transfer infrastructure to turn to for assistance.

In some cases, adoption of alternatives will occur without major disruptions to the system. In other cases, major paradigm shifts in cropping systems and marketing arrangements will be needed, and growers will have to undergo major changes and incur significant risks to stay profitable.

4.1.11 General conclusions

Soil fumigation with methyl bromide has been successfully replaced in some areas by means of methods and techniques that have been available for many years but that have been adapted or modified to suit local requirements. Additional research is needed to develop treatments that could eventually eliminate it in other areas. Because the degree of current dependency on methyl bromide varies greatly around the world, some regions may be able to substitute methyl bromide quicker than others and in some areas it is likely that it will not be possible to economically replace methyl bromide at all. In these areas it is also necessary to consider that crop systems dependent on methyl bromide may be moved to areas or other countries where such dependency does not exist or where it can be significantly reduced. These production shifts could cause serious hardship given the existing cultural and sociological considerations associated with agricultural production and consumption.

While there are many methods and materials that offer possibilities for replacement of methyl bromide, there is no single alternative available for immediate use by producers. Alternatives to methyl bromide will develop in direct response to financial investment in research needed to "ready" the alternatives for use by producers. The level of research investment required will be larger in some areas than in others. The speed with which methyl bromide can be replaced will vary according to the investment in research made by nations in areas where it is presently used. It is essential that research on alternatives (chemical, non-chemical and integrated systems) be performed thoroughly and in a wide range of climatic and geographical locations. This is essential to avoid substitution of methyl bromide by fumigation or treatment with other chemicals, or by other methods, which may be more damaging to human health and the environment than methyl bromide.

4.1.12 References

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Case history 4.1.1: Methyl bromide reduction and elimination in horticultural production in Italy

Crops: Fruits, Vegetables, Flowers, Plants[a]

Pests: Soil-borne diseases, especially those caused by the *Rhizoctonia, Phytophthora, Pythium, Fusarium*, and *Thielaviopsis*[b].

Geographic areas:

Region 1: Lake Bracciano Area (Bracciano, Trevignano and Anguillara municipalities);

Region 2: Emilia-Romagna region[c];

Region 3: Emilia-Romagna Cooperatives

Region 1: Lake Bracciano

Alternatives: Chemical products, steam, solarisation, crop rotation, intercropping and biological control.

Until 1983, methyl bromide was heavily used in fields and greenhouses surrounding Lake Bracciano, located in Bracciano, Trevignano and Anguillara municipalities, in the province of Rome. The area is intensively cultivated, especially near the lake shore in Trevignano municipality where vegetables are grown in plastic greenhouses. This region is in central Italy. General climatic information includes an average rainfall each year of 749 L/m^2, an average of 2491 hours of sunshine each year with 56 percent of the days being cloudy. Latitude and longitude are approximately 41 and 12 degrees, respectively. Average height above sea level is 125 meters[d].

A prohibition was placed on the use of methyl bromide in this area, by Regional Ordinance (No. 288, 3rd August 1983), because of concerns about contamination of the water carried from lake Bracciano to the city of Rome.

Lazio Region gave funds to farmers to compensate the main costs of applied treatments; the first alternative applied was steam sterilisation. Ersal (a Regional body for agriculture development) purchased steam machinery and organised soil treatment in the area.

Steam treatments were considered too expensive and in order to find a better alternative to steam, ENEA (the Italian Commission of Innovation Technology, Energy and Environment) and A.G.E.R. (an agricultural advice cooperative) conducted a research program over several years, to study the feasibility of soil solarisation in the Bracciano lake area. The research was carried out on 14 horticultural farms, comprising 2.8 hectares of greenhouses (out of a total of 12 hectares in the zone), and 9.2 hectares of open fields.

[a] General information about crop production, specifically the number of cropping cycles per year, was not available.

[b] Although the authors were not available to provide specific species names, typical horticultural pest species are included.

[c] General climatic information was not available.

[d] Rudolf, Willie., World-Climates: With Tables of Climatic Data and Practical Suggestions, Wissenschaftliche Verlagsgesellschaft: 1981.

Solarisation involves laying plastic film on the soil to enhance the sun's heat and kill certain soil organisms. The researchers found that solarisation had an important impact in inhibiting weeds and fungi, but was not sufficiently effective as a nematicide. However, good results were obtained by combining solarisation with Integrated Pest Management, including the use of organic substances and compost, agronomic techniques, and selected and targeted use of low toxicity pesticides.

The combination of solarisation with other cultural techniques has given very positive technical results. Yield has not been reduced, and in some cases yield has increased. The combined method has been so successful that it will be applied to other parts of the Lazio region. The method received a favourable reaction from local farmers, from the perspectives of economics, environmental protection, and health protection.

Solarisation is most effective in the Southern Regions of Italy (where methyl bromide is used heavily at present). In these Regions, it is common agricultural practice to suspend cultivation for about one month during the warmest period, so effective solarisation treatment is feasible. But for many crops, solarisation is likely to be more effective if it is combined with other cultural practices.

Cost and yield implications: The cost of the combined solarisation/IPM method is very low compared to methyl bromide use or steam. Cost of solarisation in the Bracciano lake area is about 800,000 - 900,000 liras per hectare (around US$ 550-600).

Region 2: Emilia-Romagna regional program

Alternatives: Reducing methyl bromide applications by 50 percent.

The Agricultural Regional Authorities in this region have promoted several regional programs to control the use of pesticides since the 1970s. The most recent Integrated Production Regional Program involved 20 percent of fruit growers and seven percent of vineyard growers by 1991. The program prescribes a code of production (the Integrated Crop Management Code of Production) which specifies the technical methods to be used. The Code limits the use of methyl bromide to one fumigation in every two years. As a result, growers on at least 20,000 hectares have reduced the use of methyl bromide by 50 percent.

Cost and yield implications: The price of each methyl bromide fumigation in the Emilia-Romagna area is 6 million liras per hectare (about US$3,700). Limiting the frequency of fumigations has saved farmers considerable expenditure.

Estimation of methyl bromide being replaced: The Emilia-Romagna region uses considerable quantities of methyl bromide (670 t in 1990). Twenty percent of fruit growers and 7 percent of vineyard growers comprising a total of 20,000 hectares of agricultural land have reduced methyl bromide use 50 percent.

Region 3: Emilia-Romagna Cooperatives

Alternatives: Strip fumigation with methyl bromide only on land intended for planting.

Several farmers' cooperatives in the Emilia-Romagna region have developed the Regional Program further. The APO cooperative has adopted a technique that allows a greater reduction in methyl bromide use, by fumigating soil only on the strip of land where plants will be planted.

Estimation of methyl bromide being replaced: This technique is applied to almost 100 hectares of strawberries. The technique uses 60 percent of the amount of methyl bromide used for an entire field.

Cost and yield implications: Taking account of the biannual treatment, the total reduction in methyl bromide use has been 70 percent, according to the cooperative's technical advisers. The results of cutting methyl bromide were monitored, and the cooperative found there were no losses in yield, and that the cost savings were quite high.

Documentation: Dr. L. Cori+ and Prof. L. Triolo*, " Review of Cases of Methyl Bromide Reduction and Elimination in Italy," January 1994, unpublished paper.

(+COSPE, Bologna; *Biotechnology and Agriculture Sector, Technology Innovation Department, ENEA, Rome).

Case history 4.1.2: Forest tree nurseries in the People's Republic of China

Crop

Forest nurseries. The most abundantly produced trees are *Pinus* (22 species), *Picea* (19 spp.), *Larix* (10 spp.), *Cunninghamia lanceolata* (Chinese fir), *Populus* spp., *Salix* spp., *Ulmus* spp.

Pests

Numerous fungi, including *Rhizoctonia solani*, *Pythium* spp., *Fusarium* spp., *Macrophomina phaseolina*, *Sclerotium rolfsii*, and *Rosellinia necatrix*; bacteria, including *Agrobacterium tumefaciens*; nematodes, including *Meloidogyne* spp.; and insects, including *Otiorrhynchus* spp. (root weevils), *Agrotis* spp., *Paria* spp. (rootworms), *Pantomorus cervinus*, *Euxoa* spp. *Gryllotalpa* spp. (mole cricket).

Geographic area

Seedlings are grown in nurseries throughout China. In North China, primarily temperate species are grown, especially *Populus* spp. (poplars and aspens), *Salix* spp. (willows), *Ulmus* spp. (elms), and *Pinus tabulaeformis*. In South China, primarily sub-tropical species are grown, especially *Cunninghamia lanceolata* (Chinese fir), *Pinus massoniana* (Massonia pine), and numerous species of sub-tropical hardwoods.

Alternatives

The People's Republic of China uses no methyl bromide in the production of tree seedlings for forestry. A combination of methods is used as part of an IPM strategy.

Crop rotation and fallowing, burning, soil solarisation, and repeated ploughing and raking of the soil are all used to reduce pest levels before seedlings are planted.

Seed treatments are used to disinfest seeds prior to planting. Treatments include formalin, sodium hypochlorite (bleach), potassium permanganate, hot water, and a botanical extract from *Stellaria chamaejasme*.

The following botanicals are used especially to reduce damping off fungi and soil-borne insects:

Melia azadarach, Aleurites fordii (tung), *Camellia sasangua, Rhododendron molle, Polygonum nodosum, Tripterygium wilfordii, Daphne genkwa*, and rotenone.

Beneficial micro-organisms also are widely used. They are applied to both seeds and to seedling roots during transplanting. Most commonly used are *Arthrobotrys oligospora* (for control of root knot nematodes), *Trichoderma harzianum, Bacillus cereus*, and *Actinomyces* 5406.

Comments

Each year some 204,000,000 seedlings are grown to plant approximately 6 million ha. The total area used for forest nurseries is about 241,200 ha, but because crop rotation is practiced only about one-half of this area is planted with seedlings at any one time. Of the total area, 42,800 ha are state nurseries, 85,300 ha are collectively owned, and 113,100 ha are privately owned.

Typical production yields and costs are described in Table 4.1.1:

Table 4.1.1 Production Yields and Costs for Forest Tree Nurseries in the PRC

Species	Production (seedlings / hectare)	Costs (US$ / ha)
Cunninghamia lanceolata (Chinese fir)		
cuttings	1,200,000 to 1,350,000	$445 to 500
seedlings	1,800,000	$445 to 500
Pinus tabulaeformis (Chinese Pine)		
one year	2,250,000 to 2,400,000	$500
two year	1,125,000 to 1,350,000	$500
Populus spp. (Poplar)		
cutting	60,000 or 150,000	$1420

Documentation:

Cheng, Wan Jun, *et al*., editors. 1981. The Silviculture of Main Chinese Trees. China Forestry Publishing House, Beijing. 1342 pp. [In Chinese].

Personal communications with Momei Chen, Professor of Forest Pathologist (retired), Chinese Academy of Forestry, Beijing, People's Republic of China; and Anghe Zhang, Professor of Forest Management (retired), Chinese Academy of Forestry, Beijing, People's Republic of China.

Scientific and Technological Information Center, Ministry of Forestry, China. 1991. Development of Forestry Science and Technology in China. China Science and Technology Press, Beijing. 205 pp.

Wang, Yung Zhang, Momei Chen, *et al*. eds. 1982. The Forest Diseases of China. China Forestry Publishing House, Beijing. 254 pp. [In Chinese].

Case history 4.1.3: Alternatives in forest tree nurseries in the USA (Pacific Northwest) and Western Canada

Crop

Forest nurseries. The most abundantly produced species are Ponderosa pine (*Pinus ponderosa*), Scots pine (*Pinus sylvestris*), Colorado spruce (*Picea pungens*), and Douglas fir (*Pseudotsuga menziesii*)

Pest

Weeds, and plant-pathogenic fungi in the genera *Pythium*, *Fusarium*, *Phytophthora*, and *Rhizoctonia*.

Geographic area

Forest nurseries of the northwestern USA and adjacent Canada.

Alternative

Soil fumigation with dazomet (Basamid®), or metam sodium.

Campbell and Kelsas found seedling growth and survival were as good after pre-plant fumigation with dazomet or metam-sodium as with methyl bromide-chloropicrin mixtures. Furthermore, seedlings grown in dazomet treated soil showed greater uniformity of height and diameter than with the other fumigants.

Scholtes describes use of dazomet as a replacement for methyl bromide/chloropicrin fumigation at the nursery he manages. Douglas fir is the primary species grown on 213 acres of seedling production land. The nursery produces approximately 21 million seedlings annually. Methyl bromide was used starting in 1978, but use was greatly reduced starting in the mid-1980s due to concerns about increasing regulations on methyl bromide, difficulties with disposal of plastic tarps, and poor contractor safety and performance. Dazomet has proved quite satisfactory, the only limitation being phytotoxicity to Western White Pine caused by the containment of vapours during periods of climatic thermal inversions. The problem has been avoided by planting Western White Pine upwind from the treatment sites, and by using large buffer zones around these sensitive seedlings.

Alspach describes the success of dazomet for soil fumigation at a nursery in Canada. Trials began in 1963, and the material is currently in routine use. This nursery produces 7 to 10 million trees annually and ships seedlings to clients throughout the Canadian prairies, primarily in Manitoba and Saskatchewan.

Similarly, McElroy describes studies on the successful use of both dazomet and metam-sodium at three nurseries over a three year period in the mid-1980s. He concludes that both materials gave control equivalent to methyl bromide-chloropicrin.

Economic data for these production systems not available. However, according to Scholtes, USDA Forest Service Nurseries are required to be self-supporting, including paying government labour rates which are considerably higher than those paid in the private sector.

Who now uses the alternative?

Several forest nurseries operated by the United States Department of Agriculture Forest Service and Agriculture Canada.

Comments

Researchers and forest nursery managers have found dazomet and metam-sodium to be effective alternatives to fumigation with methyl bromide/chloropicrin. Cost of applying dazomet and metam-sodium are considered to be equal to or less than methyl bromide-chloropicrin.

Documentation:

Oral presentations, published in Scholtes (1989).

Alspach, L.K. 1989. Dazomet use for seedbed fumigation at the PFRA Shelterbelt Centre, Indian Head, Saskatchewan. General Technical Report RM-184, Rocky Mountain Forest and Range Experiment Station, United States Department of Agriculture Forest Service, Fort Collins, Colorado, USA. 40-42.

Campbell, S.J., and B.R. Kelpsas. 1988. Comparison of three soil fumigants in a bareroot conifer nursery. Tree Planters' Notes (USDA Forest Service, Washington, D.C.), 39(4):16-22.

McElroy, F.D. 1986. Use of metam-sodium and dazomet fumigants. General Technical Report RM-137, Rocky Mountain Forest and Range Experiment Station, United States Department of Agriculture Forest Service, Fort Collins, Colorado, USA, 139-146.

Scholtes, J.R. 1989. Soil fumigation at J. Herbert Stone Nursery. General Technical Report RM-184, Rocky Mountain Forest and Range Experiment Station, United States Department of Agriculture Forest Service, Fort Collins, Colorado, USA, 35-37.

Scholtes, J.R. 1994. Personal communication.

Case history 4.1.4: Use of alternatives in vineyards in California, USA

Crop

Grapes (*Vitus vinifera*)

Pest

Numerous soil-borne pests, including weeds, nematodes, fungi (especially oak root fungus *Armillaria mellea*), and insects (especially the root aphid *Phylloxera*).

Geographic area

All of the grape growing areas of California. California is one of the premier wine regions of the world.

Alternatives

A number of control measures are used, including cover crops (especially cereal rye, alfalfa, and Sesbania), rootstocks resistant to *Phylloxera* and nematodes, application of composts and manures to encourage beneficial soil microorganisms, monitoring to identify areas of the vineyard in need of particular treatments, subsoil plowing and ripping, fallow and rotation periods prior to replanting grapes. In addition, some growers feel fumigation is unnecessary at some sites despite presence of pest populations at varying levels.

Who now uses the alternative?

Many wine grape growers in California, including some of the largest and best known in the world, have areas that are not fumigated. Growers include such well-known producers as Frey, Fetzer and Gallo, as well as smaller growers. Grapes from these vineyards are used to produce wines of all qualities, including some of the finest wines from the region.

Comments

As of 1992, there were 137,085 ha of wine grapes grown in California. While soil fumigation is commonly practiced in some California vineyards, it is by no means universally practiced. The number of acres fumigated with methyl bromide vary widely depending on a number of factors including crop and pest history, region of the state, grower preference, etc. In 1992, of the 3,096 acres of winegrapes planted, only 41% (1,264 acres) were fumigated with methyl bromide. Data on yields and other economic parameters are proprietary and were not made available.

Documentation

Interviews with vineyard owners and managers, and crop consultants associated with vineyards in California:

Fetzer Vineyards, Hopland
Frey Vineyards, Mendocino County
Greg Coleman, Gallo Vineyards
Phil Phillips, Area IPM Advisor, Cooperative Extension, Ventura County
Sahatdgian Farms, Madera
Soghomonian Vineyards, Fresno

California Agricultural Statistics Service. 1992. California Grape Acreage 1992. California Dept. Food and Agriculture, Sacramento, CA.

Dept. of Pesticide Regulation. 1993. Annual Pesticide Use Report 1992. California EPA, Sacramento, CA.

Case history 4.1.5: Replacement of methyl bromide use in horticultural nurseries, Ohio

Crop

Horticultural and vegetable nursery plants.

Pest

Soil-borne diseases, especially those caused by the fungi *Rhizoctonia*, *Phytophthora*, *Pythium*, *Fusarium*, and *Thielaviopsis*.

Geographic area

Ohio, USA

Alternative

Composted hardwood barks as a potting soil amendment.

Who now uses the alternative?

Widely practiced by nursery growers in Ohio on crops as varied as chysanthemums, Christmas trees, cut flowers, and vegetables. Some of these operations are among the largest of their kind in the USA. The combination of antifungal substances in young bark compost, and biocontrol organisms in mature bark composts, effectively control soil pathogens.

Comments

Starting in the 1970s, the use of compost replaced virtually all uses of methyl bromide in the Ohio nursery industry. In contrast, nursery growers in California use more than 900 t of methyl bromide annually.

Documentation

Hoitink, H.A.J., and G.A. Kuter. 1985. Effect of composts in container media on diseases caused by soilborne plant pathogens. Acta Horticulturae, 172, 191-197.

Hoitink, H.A. 1994. Ohio State University, Wooster, OH 44691, USA. Personal communication.

Moore, L.W. 1983. Composted bark, chrysanthemums, and Christmas trees. Plant Disease, 67, 706.

Case history 4.1.6: Organic strawberries in California

Crop

Strawberry (*Fragaria* x *ananassa*)

Pests

Numerous other soil-borne pests, including fungi (especially *Verticillium dahliae*, *Phytophthora fragariae*, *Phytophthora* spp., *Pythium* spp.), nematodes (especially root knot nematodes in the genus *Meloidogyne*), weeds, and the complex responsible for black root rot disease.

Geographic area

Coastal California, which produces some of the largest yields in the world.

Alternative

Each year, roughly 2,000 t of methyl bromide are used on California strawberries. This accounts for 3% of the world's total use of methyl bromide.

Organic strawberry growers in California do not use methyl bromide as a pre-plant soil fumigant (although they do use transplants grown in soil treated with methyl bromide and chloropicrin). They control weeds and reduce losses to soil borne diseases using a combination of methods including cover crops, crop rotation, and acceptance of lower yields in return for higher prices at the supermarket.

Who now uses the alternative?

In California, twenty-two organic farms currently produce strawberries without methyl bromide. Most consider their operations profitable. One of the best documented is Swanton Berry Farms, on California's central coast near Santa Cruz.

Comments

Yields in organic production are about 65% that of conventional production. However, currently, organic strawberries sell for approximately twice the price of conventional berries, and this offsets the lower yield. Fruit quality is considered quite good, although organic fruit may be slightly smaller. The growers who do not use methyl bromide are all certified organic, and therefore cannot use synthetic pesticides and fertilisers. This sometimes leads to increased pest problems, especially mites and lygus bugs, and to difficulty regulating the timing of nitrogen applications. Conventional growers who stopped using methyl bromide would not face these constraints and could achieve higher yields. In experimental plots where no fumigation was used but other production parameters were conventional, yield of non-fumigated plots was 72% that of fumigated plots. However, the prior cropping and/or fumigation history of the non-fumigated plots used in these trials is not known. Table 4.1.2 compares production data on conventional fumigated strawberries and non-fumigated organic strawberries.

Table 4.1.2 Comparison of Conventional and Organic Strawberry Production in California, USA.

Type of Production	Typical Yield ($t\ ha^{-1}$)	Fumigation with Methyl Bromide	Production Cycle	Rotation
Conventional	60	yes	annual	1 crop every year or every other year
Organic	40	no	annual and perennial	1 to 2 crops every 4 to 5 years

Documentation

California Certified Organic Farmers, Santa Cruz, CA 95060 USA.

Cochran, J. 1994. Swanton Berry Farms, Davenport, CA, USA. Personal communication.

Gliessman, S. R. *et al.*, 1990. Strawberry production systems during conversion to organic management. California Agriculture, 44, 4-7.

Liebman, J.A. 1994. Alternatives to methyl bromide in California strawberry production. IPM Practitioner, 7(16); 1-12.

Webb, R. 1994. Driscoll Strawberry Research, Watsonville, CA, USA. Personal communication.

Welch, N.C. and J.A. Beutel. 1990. Strawberry production and costs in the central coast of California. Agric. Extension, University of California. 8 pp.

Annex 4.1.1

Methyl bromide soil fumigation use survey

The following tables and figures represent data on methyl bromide consumption for soil fumigation applications from a variety of sources including responses to a survey distributed by the Methyl Bromide Technical Options Committee (MBTOC) and industry estimates from various sources. The survey was sent in 1994 to 122 signatories of the Montreal Protocol. The number of responding countries totalled 39, representing a 32 percent response rate. Industry estimates for nine additional countries supplement the survey data. Methyl bromide use as a soil fumigant is reported for a total of 48 countries.

The collected use statistics are provided in the following pages. First, a table (Table 4.1.3) is presented that identifies countries responding to the survey, whether methyl bromide is used in responding countries as a soil fumigant, and whether crop-specific data were available on methyl bromide use. The second table (Table 4.1.4) details the crop specific data for each country for which data were available. As the table indicates, 50,913 t of methyl bromide were used for soil fumigation in the listed countries. Not all countries reported the number of hectares treated with methyl bromide, but for those that did, a total of 130,034.8 hectares were treated.

The reported consumption of the 48 responding countries, 50,913 t, accounts for roughly 89 percent of the annual worldwide production of methyl bromide for soil fumigation applications based on the latest (1992 data) reported figures. In 1992, it was estimated that 75,625 t of methyl bromide were produced worldwide for all applications, of which 57,407 t were for soil fumigation (i.e., pre-plant) applications.

Following the tables, six pie charts (Figures 4.1.1 - 4.1.6) are presented. The first, Figure 4.1.1, indicates those countries with the greatest use by volume including U.S.A., Italy, Japan, Spain, Israel, France, Brazil, Turkey, and Greece. The following charts distribute international methyl bromide use among the major use categories. The figures present data for the world, U.S.A. alone, and the rest of the world (excluding U.S.A.). As the figures indicate, soil fumigation usage with methyl bromide is greatest for tomatoes, strawberries, cucurbits, peppers, and tobacco.

The following assumptions were made in compiling the tables and figures:

- Use statistics from Canada, Denmark, and U.S.A. were for 1992, but were assumed to remain constant.

- Certain crops were grouped into categories. These groupings are:

Berries:	Blackberries, boysenberries, raspberries
Citrus fruits:	Grapefruit, lemon, orange, tangerine
Cucurbits:	Cucumbers, melons, pumpkins, squashes
Nuts:	Almonds, pecans, walnuts

Table 4.1.3 Responses to MBTOC survey on methyl bromide use as soil fumigant

Countries reporting use	Countries reporting no use	Countries reporting use, but not use volume	Countries reporting use volume, but not by crop
Australia	Bangladesh	China	Argentina
Austria	Bulgaria	Peru	Brazil
Bahamas	Finland		Chile
Belgium	Germany		Colombia
Canada	India		El Salvador
Denmark	Mauritius		Thailand
Egypt	Namibia		Uruguay
France	Netherlands		
Greece	Norway		
Israel	Republic of Korea		
Italy	Romania		
Japan	Sweden		
Jordan	Taiwan		
Kenya	Tunisia		
Malaysia	Tuvalu		
Malta	Uganda		
Morocco	West Indies (St. Lucia, St. Kitts)		
Saudi Arabia			
South Africa			
Spain			
Turkey			
U.K.			
U.S.A.			
Zimbabwe			

Table 4.1.4 MBTOC survey results. Methyl bromide use as soil fumigant by country and use sector

Country	Data Source	Crop	Treated Area (hectares)	MeBr used (t)	Percentage of total crop treated	Data year
Argentina	4	Not specified	NA	245	NA	1993
Australia	1	Cut Flowers	NA	146	NA	1993
		Fruit	NA	117	NA	1993
		Turf	NA	24	NA	1993
		Vegetable	> 300	319	>10	1993
		Total:		606		
Austria	1	Fruit and gardening	7	3.4	0	1993
Bahamas	1	Cantaloupe	27	29	100	1993
		Green peppers	12	5	100	1993
		Tomatoes	77	61	100	1993
		Watermelon	11	7	100	1993
		Total:		102		
Belgium	1	Flowers	NA	60	NA	1993
		Melons	NA	0	NA	1993
		Nurseries	NA	60	NA	1993
		Pepper, Eggplant, Cucumber	NA	40	NA	1993
		Potting Soil	NA	12	NA	1993
		Strawberries	NA	20	NA	1993
		Tomatoes	NA	200	NA	1993
		Other	NA	8	NA	1993
		Total:		400		
Brazil	4	Not specified	NA	1,120	NA	1993
Canada	1	Fruits & vegetables	NA	66.6	NA	1991
		Ornamentals	NA	0.3	NA	1991
		Strawberries	NA	10.0	NA	1991
		Turf and forestry	NA	0.8	NA	1991
		Total:		77.7		
Chile	5	Tomatoes, peppers and chilies	NA	260	NA	1993
Columbia	4	Not specified	NA	102	NA	1993
Denmark[a]	1	Cut flowers	1.9	1.7	5	1992
		Lettuce	> 2.0	0.7	> 13	1992
		Tomatoes	20.5	20.4	34	1992
		Other vegetables[b]	1.2	1.2	12	1992
		Total:		24		
Egypt	1	Cucumbers	100	50	25	1993
		Strawberries	100	50	5	1993
		Total:		100		
El Salvador	4	Seedbed nurseries	NA	95.4	NA	1993
France	2	Flowers	NA	195	NA	1993
		Melons	NA	75	NA	1993
		Nurseries	NA	75	NA	1993
		Pepper, eggplant and cucumbers	NA	225	NA	1993
		Potting soil	NA	75	NA	1993
		Strawberries	NA	375	NA	1993
		Tomatoes	NA	450	NA	1993
		Other	NA	30	NA	1993
		Total:		1,500		

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[a] In 1993, Denmark used 13 metric tons of methyl bromide for soil fumigation.

[b] Other vegetables include: sweet pepper, parsley, radish, carrots, cabbage, and eggplant.

Table 4.1.4 (cont.) MBTOC survey results. Methyl bromide use as soil fumigant by country and use sector

Greece	3	Cucumber	NA	125	NA	1993
		Green pepper	NA	100	NA	1993
		Tobacco seedbeds	NA	125	NA	1993
		Tomatoes	NA	600	NA	1993
		Total:		950		
Israel	1	Carrots	NA	100	NA	1993
		Cucumbers	NA	340	NA	1993
		Eggplants	NA	75	NA	1993
		Flowers	NA	745	NA	1993
		Green herbs	NA	36	NA	1993
		Legumes	NA	112	NA	1993
		Melons	NA	245	NA	1993
		Orchards	NA	15	NA	1993
		Peppers	NA	220	NA	1993
		Potatoes	NA	400	NA	1993
		Strawberries	NA	180	NA	1993
		Tomatoes	NA	200	NA	1993
		Zucchini	NA	50	NA	1993
		Total:		2,718		
Italy	2	Flowers	NA	700	NA	1993
		Melons	NA	700	NA	1993
		Nurseries	NA	350	NA	1993
		Pepper, eggplant and cucumbers	NA	1,050	NA	1993
		Potting soil	NA	210	NA	1993
		Strawberries	NA	1,050	NA	1993
		Tomatoes	NA	2,800	NA	1993
		Other	NA	140	NA	1993
		Total:		7,000		
Japan	1	Bed soil	NA	359	NA	1992
		Broccoli	1.7	0.5	>1	1992
		Butterbur	5.0	3	>1	1992
		Cabbage	119.8	36	>1	1992
		Carnation	13.2	8	2	1992
		Celery	2.6	0.6	>1	1992
		Chestnuts	9.9	3	>1	1992
		Chive	104.0	63	5	1992
		Chrysanthemum	158.4	56	3	1992
		Cucumber	1,244.1	522	12	1992
		Eggplant	178.2	92	1	1992
		Chinese bell and other flowers	95.7	30	14	1992
		Ginger	108.9	33	3	1992
		Green soybeans	3.3	1	>1	1992
		Kidney beans	29.7	9	>1	1992
		Lettuce	3.3	1	>1	1992
		Melon	2,107.0	741	12	1992
		Okra	47.9	16	NA	1992
		Onions	227.7	69	NA	1992
		Oranges	6.6	2	>1	1992
		Other flowers	277.2	120	1	1992
		Peanuts	3.3	1	>1	1992
		Peas	23.1	7	4.4	1992
		Pepper	589.6	272	13.0	1992
		Pumpkins	62.7	19	>1	1992
		Radish	145.2	44	>1	1992
		Rice	23.1	7	>1	1992
		Scallions	9.9	3	>1	1992
		Spinach	5.0	3	>1	1992
		Strawberries	915.1	325	9	1992
		Sweet Potatoes	174.9	53	>1	1992

Table 4.1.4 (cont.) MBTOC survey results. Methyl bromide use as soil fumigant by country and use sector

Japan (cont.)		Tobacco seedbeds	92.4	28	>1	1992
		Tomatoes	754.1	322	5	1992
		Turnips	79.2	24	1	1992
		Watermelons	2,650.9	963	12	1992
		Others	NA	2,127	NA	1992
		Total:		6,363		
Jordan	1	Vegetables and seed bed plantings	3,360	280		1993
Kenya	4	Floriculture and strawberries	NA	137	NA	1993
Malaysia	1	Tobacco seedbeds/Other	< 0.1	< 0.1	NA	1993
		Turf	2.3	1.2	NA	1993
		Total:		1.3		
Malta	1	Cucumbers	NA	8	50	1993
		Eggplants	NA	5	80	1993
		Flowers	NA	5	100	1993
		Peppers	NA	7	50	1993
		Strawberries	NA	8	100	1993
		Tomatoes	NA	7	100	1993
		Total:		40		
Morocco	3	Melons	NA	100	NA	1993
		Strawberries	NA	100	NA	1993
		Tomatoes	NA	400	NA	1993
		Total:		600		
Saudi Arabia	1	Tomatoes, cucumbers and dates	450	200	8	1993
South Africa	1	Apples, pears	800	133	1.5	1993
		Flowers (ornamental)	795	71	35	1993
		Nurseries	160	6	100	1993
		Strawberries	258	32	67	1993
		Tobacco seedbeds	2,125	170	100	1993
		Vegetables	802	41	1	1993
		Total:		453		
Spain	1	Carnations	NA	50	NA	1993
		Citrus fruits	NA	40	NA	1993
		Ornamentals	NA	10	NA	1993
		Potatoes	NA	50	NA	1993
		Other fruits and vegetables	NA	1,430	NA	1993
		Strawberries	NA	1,260	NA	1993
		Total: [c]	NA	2,840	NA	1993
Thailand	1	Not specified	NA	0.2	NA	1993
Turkey	3	Flowers	NA	150	NA	1993
		Tomatoes	NA	800	NA	1993
		Total:		950		
United Kingdom	1	Chrysanthemum, other flowers	12	9	4.4	1993
		Cucumber	2	2	< 1	1993
		Lettuce	40	28	2.7	1993
		Nursery Stock	2	2	< 1	1993
		Strawberries	500	350	30	1993
		Tomatoes	50	35	10.0	1993
		Total:		425		

[c] According to industry estimates, the total figure for MeBr use in Spain in 1993 was approximately 4,000 tonnes.

Table 4.1.4 (cont.) MBTOC survey results. Methyl bromide use as soil fumigant by country and use sector

United States	1	Apples	645	119	< 1	1992
		Berries	33	9	0	1992
		Broccoli	185	39	< 1	1992
		Carrots	847	162	2	1992
		Cauliflower	200	46	< 1	1992
		Cherries	827	82	2.1	1992
		Citrus	1,031	132	NA	1992
		Curcurbits	2,145	473	NA	1992
		Eggplant	810	181	58.8	1992
		Other fruits and vegetables	2,301	404	NA	1992
		Forest seedlings, seedbeds and grass	2,167	764	NA	1992
		Grapes	2,264	876	< 1	1992
		Lettuce	640	149	< 1	1992
		Nuts	10,131	770	NA	1992
		Peaches	1,381	323	1.9	1992
		Peppers	9,292	2,041	23	1992
		Plants	3,644	1,678	NA	1992
		Plums and Prunes	1,028	86	2	1992
		Potatoes	97	39	0	1992
		Strawberries	13,645	2,507	68	1992
		Sweet Potatoes	2,891	595	9	1992
		Tobacco seedbeds	3,360	1,678	3	1992
		Tomatoes	22,267	5,062	12	1992
		Other	24,697	4,536	NA	1992
		Total:		22,716		
Uruguay	4	Not specified	NA	4	NA	1993
Zimbabwe	1	Curcurbits	50	4	NA	1993
		Greenhouse flowers	60	6	NA	1993
		Roses	130	12	NA	1993
		Shadehouse flowers	60	6	NA	1993
		Strawberries	40	4	NA	1993
		Summer flowers	200	19	NA	1993
		Tobacco seedbeds	1,100	550	NA	1993
		Total:		601		
Total			128,460	50,913	-	-

Data sources:

1. Survey data collected by Methyl Bromide Technical Options Committee from Agricultural Ministries and Departments of Environment, 1994.
2. Industry estimates prepared by Eurobrom, 1994.
3. Industry estimates prepared by Bromine Compounds Ltd., 1994.
4. Okioga, David, 'Survey of Methyl Bromide Use in Article 5 Countries', 1994, Kenya Agricultural Research Institute, 1994.
5. Fernandez, Juan Francisco, 'Data on Imports of Methyl Bromide Compiled from Importers and Customs Office', Department of Sustainable Development, Chile, 1994.

Figure 4.1.1. Global methyl bromide use for soil fumigation - by country. 1992. MBTOC survey data.

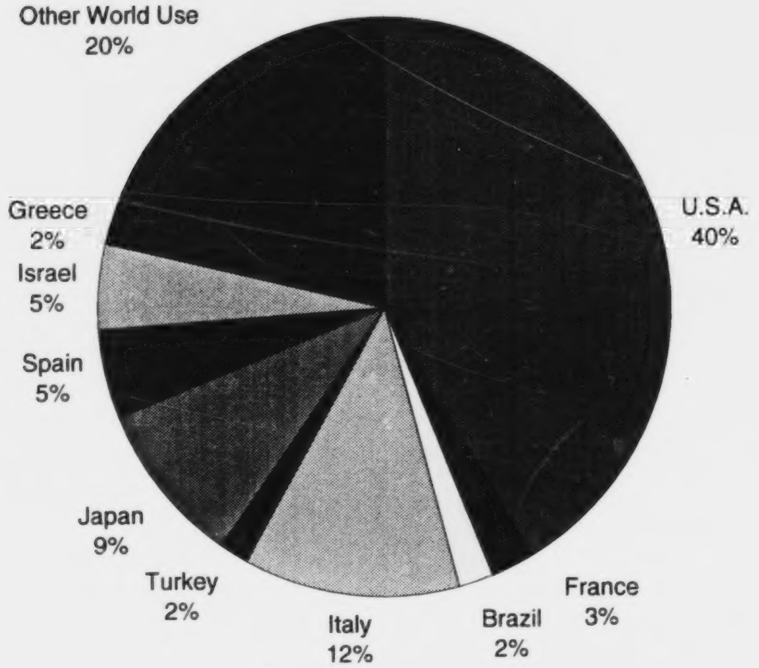


Figure 4.1.2. Global use of methyl bromide (excluding USA) for soil fumigation - by use category. 1992. MBTOC survey data.

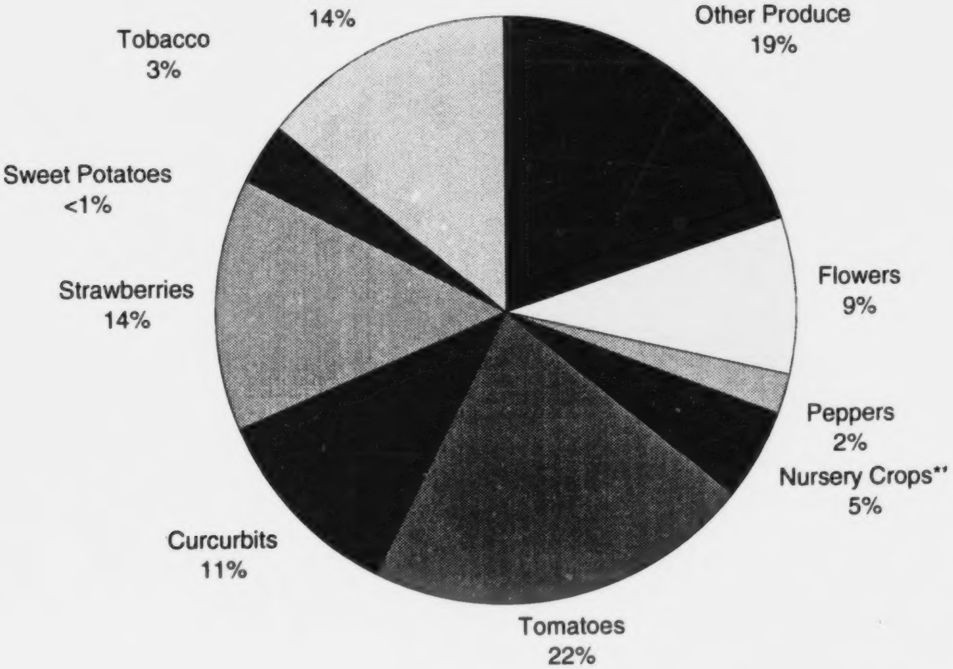


Figure 4.1.3. Use of methyl bromide in USA in 1992 for soil fumigation - by use category. MBTOC survey data.

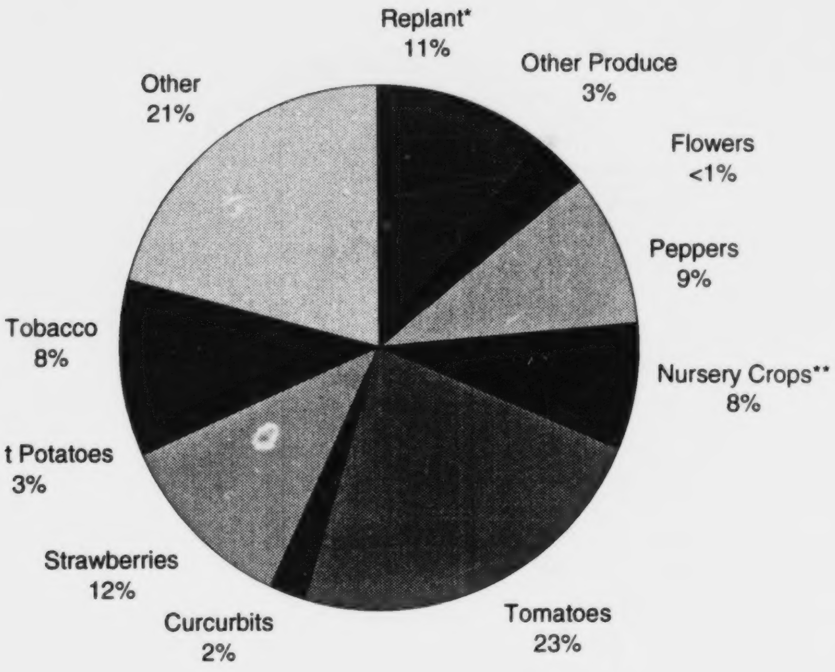


Figure 4.1.4. Global use of methyl bromide for soil fumigation - by major crop. Minor uses not included. 1992. MBTOC survey data.

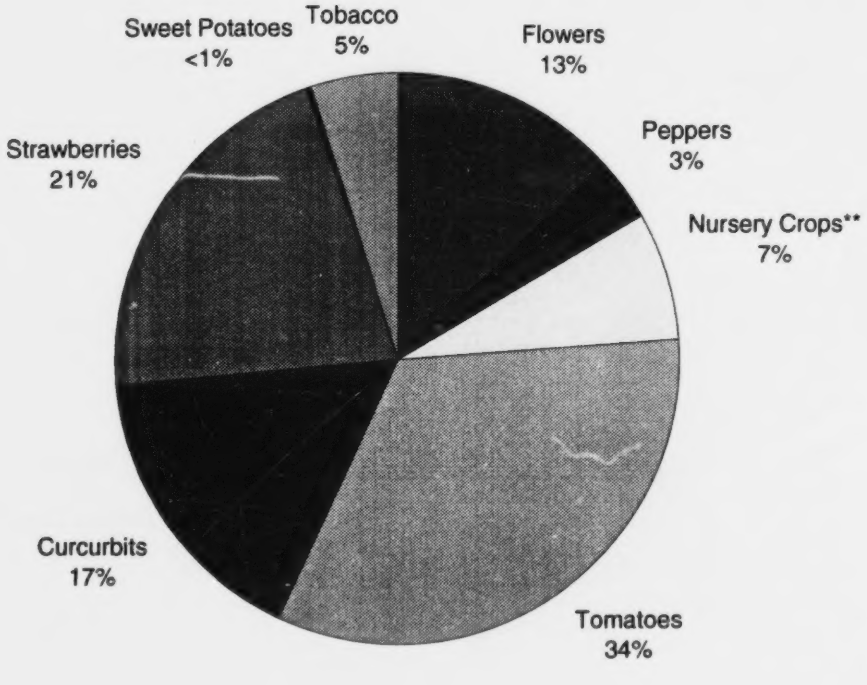


Figure 4.1.5. Global use of methyl bromide for soil fumigation (excluding USA) - for major crops only. 1992. MBTOC survey data.

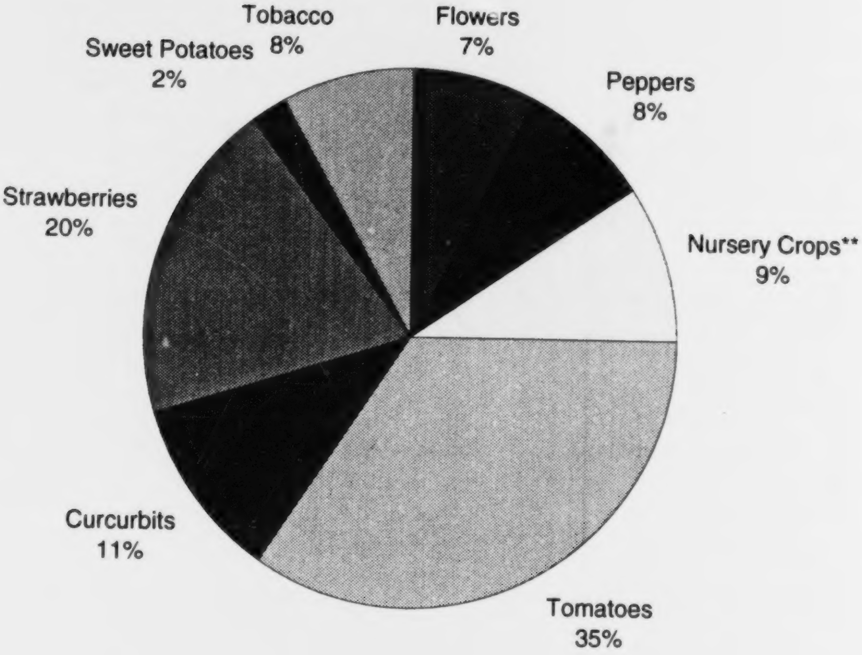
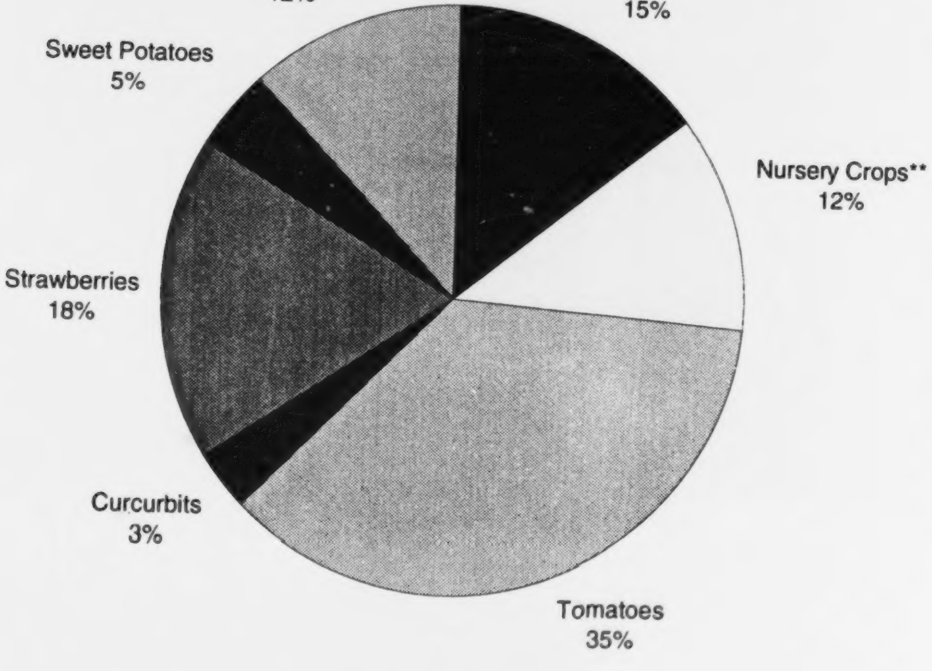


Figure 4.1.6. Use of methyl bromide for soil fumigation in USA - major crops only. 1992. MBTOC survey data.



Annex 4.1.2

Soilborne pathogens, nematodes, arthropods, and weeds controlled by soil fumigation with methyl bromide in various countries or regions of the world.

	USA	Japan	France	Spain	Israel	Mediterranean	Africa	South America
NEMATODES								
Aphelenchoides spp.	X							
Belonolaimus longicaudatus	X							
Ditylenchus spp.	X	X	X	X	X	X	X	X
Globodera spp.	X	X	X	X		X	X	X
Heterodera spp.	X	X	X		X	X	X	X
Longidorus spp.	X	X			X			
Meloidogyne spp.	X	X	X	X	X	X	X	X
Paratrichodorus spp.	X	X				X		
Pratylenchus spp.	X	X	X	X	X	X	X	X
Rotylenchulus spp.	X	X					X	X
Xiphinema spp.	X		X			X	X	X
FUNGI								
Alternaria spp.							X	
Aphanomyces spp.		X						
Armillaria spp.	X		X	X				
Clitocybe spp.	X							
Colletotrichum spp.	X					X	X	
Cylindrocladium spp.	X							
Fusarium spp.	X	X	X	X	X	X	X	X
Glomus spp.	X							
Macrophomina spp.	X				X		X	
Mucor spp.		X						
Phoma spp.	X						X	
Phymatotrichum	X						X	X
Phytophthora spp.	X	X	X	X	X	X	X	X
Plasmodiophora spp.		X						
Pyrenochaeta spp.	X	X			X	X		
Pythium spp.	X	X	X	X	X		X	X
Rhizoctonia spp.	X	X	X	X	X	X	X	X
Rhizopus spp.		X						
Rosellinia spp.	X		X	X	X			
Sclerotinia sclerotiorum	X		X	X	X	X	X	
Sclerotium rolfsii	X	X	X	X	X	X		X
Thielaviopsis spp.	X	X						X
Trichoderme viride		X						
Verticillium spp.	X	X	X	X	X	X	X	
Xylaria spp.	X							
BACTERIA								
Agrobacterium spp.	X		X	X	X			
Clavibacter spp.					X			
Erwinia spp.	X	X	X	X				
Pseudomonas spp.	X	X	X	X			X	X
Streptomyces spp.		X			X			
Xanthomonas spp.		X						

Annex 4.1.2 (cont.)

Soilborne pathogens, nematodes, arthropods, and weeds controlled by soil fumigation with methyl bromide in various countries or regions of the world.

	USA	Japan	France	Spain	Israel	Mediterranean	Africa	South America
VIRUSES								
Cucumber green mottle		X						
Cucumber mosaic			X	X				
Grape fanleaf			X					
Tobacco mosaic		X	X	X				
Tomato spotted wilt			X	X				
Wheat stripe mosaic		X						
INSECTS								
Agrotis spp.		X	X	X			X	
Frankliniella occidentalis			X					
Lyriomyza trifolii			X					
Mole crickets	X	X						
Otiorhynchus spp.			X					
Root weevils	X	X					X	
Symphylans		X						
Termites							X	
Tetranychus urticae			X				X	X
White grubs	X	X					X	
Wireworms	X	X						
WEEDS								
Broad leaf (perennial & annual)	X	X	X	X	X	X	X	X
Grasses	X	X	X	X	X	X	X	X
Sedges	X				X	X	X	X

Mediterranean = implies survey responses from Italy, Greece, Turkey
Africa = Kenya, South Africa, Zimbabwe
South America = Argentina, Brazil, Columbia, Uruguay.

Annex 4.1.3

Sample toxicological data for chemical alternatives to methyl bromide for soil treatment[a,c]

Product [CAS No.]	Acute toxicity			Skin irritation	Eye irriation	Sensi-tization	Reproduction		Genotoxicity	Oncogenicity
	LD_{50} Oral, rat (mg/kg)	LD_{50} Dermal,. rabbit (mg/kg)	LC_{50} Inhalation, rat (time) (mg/m^3)				Fertility	Teratology		
Methyl bromide [74-83-9]	214(1)	ND	1173, 8h (1)	P	P	ND	I(1)	I(1)	P(1)	I(1)
1,3-dichloropropene [542-75-6]	470(1) 127-713 (5)	504 (1,5)	3310, 4h (5)	P (5)	P (5)	P (5)	N (5)	N (5)	P (8)	IARC 2B I (5)
Anhydrous ammonia [7664-41-7]	NR	ND	1394 ppm 4h (1)	P (2)	P (2)	ND	ND	ND	I(1,4)	ND
Bromonitromethane [563-70-2]	ND	ND	ND	P (2)	P (2)	ND	ND	ND	ND	ND
Carbon bisulfide [75-15-0]	3188 (1,2)	ND	25,000, 2h (1)	P (2)	P (2,3)	ND	P (1,2)	P (1,3)	P (1)	ND
Chloropicrin [76-06-2]	250 (1)	ND	96,807, 4h (1)	P (3)	P (3)	P (3)	ND	P(8)	P (1,8)	I (5)
Dazomet [553-74-4]	320 (1)	7000 (1)	8400, 4h (1)	ND	P (1,3)	ND	ND	ND	ND	ND
Dichloro-isopropyl ether [108-60-1]	240 (1)	>2000 (1)	ND	P (2)	P (2)	ND	ND	ND	ND	IARC 3 I (6)
Ethylene dibromide [106-93-4]	108 (1) 146(6)	300 (1)	14,300 30 min (1)	P (1,2,4)	P (1,2,4)	ND	P (1,2,4)	ND	P (1,2,4)	IARC 2A (P) (1)
Formaldehyde [50-00-0]	100 (1)	270 (1,2)	203 (1)	P (2,3,4)	P (2,3,4)	P (2,3,4)	P (1,4)	N (4)	P (1,4)	IARC 2A P (1,4)
Metam-sodium [137-42-8]	450(1) 1891- 1928(6)	800(1) >3074 (6)	ND	ND	P (3)	ND	I	P (7)	P(7)	ND

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[a] This data was obtained from several databases. It is unedited. Other databases and data sources, including product manufacturers and suppliers, may have other and different data. Further data may be available from regulatory agencies. This data is provided only to show the range and complexity of assessments required to give a comprehensive view of the relative toxicity of methyl bromide and alternatives. Numbers in parentheses indicate reference from which data was obtained.

Annex 4.1.3 (cont.)

Sample toxicological data for chemical alternatives to methyl bromide for soil treatment[a,c]

Product [CAS No.]	Acute toxicity			Skin irritation	Eye irritation	Sensi-tization	Reproduction		Genotoxicity	Oncogenicity
	LD_{50} Oral, rat (mg/kg)	LD_{50} Dermal, rabbit (mg/kg)	LC_{50} Inhalation, rat (time) (mg/m^3)				Fertility	Teratology		
Methyl isothiocyanate [556-61-6]	97(2) 72(1)	33 (1,2)	1,900, 1h	P (2,3)	P (2,3)	P (2,3)	ND	N (7)	N (7)	N (7)
Propargyl bromide [106-96-7]	ND	ND	ND	P (2)	P (2)	ND	ND	ND	ND	ND
Sodium azide [26628-27-8]	27 (1)	20 (1)	ND	ND	ND	ND	ND	ND	P (1)	I (1)
Sodium tetrathiocarbonate [7345-69-9]	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Sulphur dioxide [7446-09-5]	NR	ND	5602 ppm 1h (1)	P (2)	P (2)	ND	P (1)	I (1)	P (1,4)	IARC 3 I (1)

[c] Abbreviations for toxicological effects are as follows:

P - Positive
N - Negative
I - Inconclusive
ND - No data available
NR - Not relevant

IARC Group Definitions
-2A: Animal - sufficient evidence
Human - limited evidence
-2B: Animal - sufficient evidence
Human - inadequate evidence
-3: Animal - inadequate evidence
Human - no data available

References

1. NTIS, 1993. Registry of toxic effects of chemical substances. Washington. Microfiche Edition, Quarterly Issue (July). Includes IARC and NTP references.
2. Lenga, R. E. (ed.). 1988. The Sigma-Aldrich library of chemical safety data. 2nd ed., Sigma-Aldrich Co., Milwaukee.
3. EEC Dangerous Substances Directive (67/548/EEC) (Classification, packaging, labelling).
4. The Royal Society of Chemistry. 1989-1992. Chemical safety data sheets. Vols. 1-5. Cambridge.
5. World Health Organization. 1993. Environmental health criteria 146. 1,3-dichloropropene, 1,2-dichloropropane and mixtures. Geneva.
6. Anonymous. 1991. Farm chemicals handbook '91. Meister Publishing Co. Willoghby, Ohio.
7. World Health Organization. 1994. Environmental Health Criteria for Methyl Bromide, PCS/EHC/84

Annex 4.1.4

Discussion on potential use rate reductions on methyl bromide conducted at MBTOC Bordeaux meeting and through subsequent communications among members of the Soil fumigation subcommittee

Introduction

The issue of what rate reductions in the use of methyl bromide in soils were feasible technically, and over what timescale, was put to the subcommittee first at the last 1994 meeting of MBTOC in Bordeaux. It was the feeling of the subcommittee, and its chair, that inadequate time had been allotted to discussion of this important topic. Consequently, no agreement on potential rates of reduction were achieved, and the scientific quality of the discussion on these reductions is not at a level attained elsewhere in this Report. This Annex sets out estimates based on the experience of several committee members. It reflects the divergence of opinion on the matter.

Two distinct use rate patterns emerged out of the soil fumigation subcommittee's deliberations at Bordeaux on 12 August 1994. One pattern of *high use rates* typical of some European operations involved dosages of up to 90 g m^{-2}. The other pattern, prevalent in USA, of *low use rates* at about 20 g m^{-2}. . This difference developed historically from efforts in California and Florida to reduce rates through the years in response to environmental and economic concerns and, *inter alia*, competition from other less expensive fumigants.

A second distinction that was made by the subcommittee's discussion of the problem pertained to whether in the ten-year period an all methyl bromide system was to prevail, or a system with alternatives could be developed.

Results of deliberations

No general agreement as to how much reduction in use rate could be attained was reached. However, the following calculated opinions were offered in writing by various groups and individuals who participated in the discussion. These opinions were circulated by fax by the Chair after the Bordeaux meeting of MBTOC and amendments and corrections were made by the contributors.

A. United States.

Opinion prepared by F. Westerlund, R. Webb, T. Duafala, R. Ross, R. Weber, P. Vail.

DOSAGE REDUCTION (After 10 Years - Year 2004)

Given a ten (10) year time frame, a reduction of methyl bromide dosage is presented in Table 4.1.5. These reductions are based on utilising improved application technologies (e.g. high barrier films, extending retention of methyl bromide in the soil through longer tarping periods, depth of soil injection, method of soil injection, soil types).

If, with additional research, reduced frequency of application (e.g. fumigation once each crop year vs once for each two crop years), strip application (reduced amount of soil treated to planted area only) prove effective, and with the following assumptions:

a. planting stock (root stocks, plants, seed, or other propagation material) from nurseries remain pest free.

b. alternative chemicals (e.g. 1,3-D, dazomet) retain registration or receive registration.

c. existing chemical fumigants maintain their registration.

d. current "known" pest complex remains constant and no new pests are introduced or are controlled by alternatives.

e. no known pest tolerances occur or develop.

f. It may take the full ten years before the dosage reductions as listed in Table 4.1.5 can be achieved.

Then: a % dosage reduction (Table 4.1.5) may be possible.

Table 4.1.5 Dosage Reduction in 10 Years (by 2004)

	Percent use rate reduction expected	
	Without alternatives	**With alternatives**
High rate (90 g m^{-2})	30	50
Low rate[a] (20 g m^{-2})	10	30

[a] This rate is most likely approaching the minimum rate of methyl bromide needed to achieve economic control.

These figures were developed through discussions and after considerable debate without consensus. These percentages are at the upper level of potential reduction and involve many uncertainties and estimates. Better estimates will be available from on going research to be completed in 1995.

Conclusion: On a global basis taking into account the range of application rates it is estimated that a dosage reduction between 10 to 30% on a per unit treated area basis may be achieved in 10 years. We must stress that these ranges are highly speculative. In the absence of further research, only the lower figure of 10 percent (for low dosage users) can be considered achievable. After research is completed we would be in a more informed position to assess if further reductions are possible. With increased demand, this may not permit a decrease in production for methyl bromide.

Opinion submitted by S. Daar

It is estimated that, with all available alternatives, 100% of methyl bromide use could be achieved within 10 years for many current uses.

Crops currently grown in soil fumigated with methyl bromide are also successfully grown in many locations without use of that fumigant. Use of alternative methods such as soiless substrates, crop rotation, and alternative chemicals have produced up to 100% reductions. For example:

- The Netherlands has replaced 100% use in greenhouse and field crops;
- Germany has replaced 100% use in greenhouse and field crops;
- Some regions of Italy reduced methyl bromide use by 50% to 70% or have eliminated it in some greenhouse and field crops;
- Organic growers and some conventional growers in North America, Europe, and Article 5 countries have never used methyl bromide on economically viable crops that are currently treated elsewhere with methyl bromide.

Opinion submitted by J. Curtis

The attached table describes possible reductions in methyl bromide use. The reductions are estimates based on information from the chapter in this report on alternatives to methyl bromide use as a soil fumigant and the experiences of individuals, regions and countries in eliminating or reducing methyl bromide use.

These estimates are ambitious and based on numerous factors and assumptions. The most important assumption is the availability of substantial resources for research and technology transfer. These investments are essential given that, in most countries, little effort has been thus far made to develop alternatives to methyl bromide. To ensure the long term viability of alternatives, resources should be directed toward the development and implementation of integrated strategies that combine multiple tactics for facilitating crop health. These strategies should have as their central objective the prevention of conditions that encourage pest outbreaks and should emphasise chemical treatments only as a last resort.

An additional factor influencing these estimates is the current ban on methyl bromide production and importation into the U.S.A. by the end of the year 2000. The U.S.A. is responsible for approximately 45 percent of worldwide methyl bromide use as a soil fumigant. Thus, within six years, close to half of the world's use of methyl bromide as a soil fumigant will be eliminated.

Table 4.1.6 Feasible reductions in methyl bromide soil fumigant use

Crop	Total tons used [g]	% of total MeBr used (1992/93)	% of MeBr used in soil (1992/93)	% feasible reduction by 1998	% feasible reduction by 2003
Tomatoes [a]	11,450	15.7	23.0	70	100
Peppers	2,765	3.8	5.4	70	100
Cucurbits (melons and cucumbers)	3,625	5.0	7.1	70	100
Strawberries [b]	6,552	9.0	12.9	50	100
Tobacco [c]	2,667	3.7	5.2	30	100
Nursery crops [d]	3,105	4.3	6.1	50	100
Replant [e]	2,667	3.7	5.2	50	50
Other [f]	18,082	24.8	35.5	50	85
Total MeBr use Represented:	50,913 [h]	69.8	100.0 [f]	50	90

[a] The estimates for possible reductions in methyl bromide use in vegetable production are based on the following experiences and alternatives: strip application of methyl bromide; reduced application rates of methyl bromide; previous experience in Florida tomato production with the use of 1,3-D, metam-sodium and herbicides; availability of resistant tomato varieties; the use of soil solarisation in Japanese and Italian production of tomatoes, eggplants, and cucumbers; a 100 percent reduction in methyl bromide use in greenhouse production in the Netherlands within ten years; a 40 percent reduction in greenhouse vegetable production in Denmark in two years using dazomet and artificial substrates.

These estimates are also based on the assumption that the use of 1,3-D, metam-sodium and dazomet do not cause severe phytotoxicity.

[b] The estimates for possible reductions in methyl bromide use in strawberry production are based on the following experiences and alternatives: methyl bromide use was entirely replaced in strawberry production in the Netherlands within ten years; strawberries are produced in California organically with no use of methyl bromide; production of strawberries in the other parts of the U.S.A. do not use methyl bromide; soil solarisation is used in Japanese and Italian strawberry production.

These estimates are also based on the assumption that plant breeding programs are put in place and that resistant varieties will be available in the future. In addition, in California, 10 to 30 percent lower yields are anticipated without the use of methyl bromide.

[c] The estimates for possible reductions in methyl bromide use [illegible] tobacco production are based on the following experiences and alternatives: methyl bromide [illegible] not used at all for field treatments of tobacco grown in the major tobacco-producing regions of the U.S.A. including South Carolina and North Carolina; other chemicals are available including l,3-D and metam-sodium; resistant varieties are available.

[d] The estimates for possible reductions in methyl bromide use in nursery crops are based on the following experiences and alternatives: availability of steam, soilless substrates, cross-species grafting; microbial enhancement (i.e., beneficial organisms) of potting soil; methyl bromide use was entirely replaced in nursery crops in the Netherlands; instead of methyl bromide, nursery crops in Ohio use potting soil amendments; methyl bromide is not used in forest tree nurseries in China; other fumigants and pesticides such as metam-sodium are available.

These estimates are based on the assumption that adequate consideration is given to eliminating industry resistance to changing conventional practices. In the nursery, methyl bromide is generally considered inexpensive.

[e] The estimates for possible reductions in methyl bromide use in replant crops (stone fruits, citrus, vineyards, nuts and berries) are based on the following alternatives and experiences: methyl bromide is not used in many vineyards in California; other fumigants and pesticides are available; solarisation can be used in combination with other techniques; crop rotations have been demonstrated to be effective alternatives.

[f] The "Other" category includes sweet potatoes, flowers and all commodities reported to MBTOC simply as "other" or "other produce". For the purpose of developing a phase-out schedule, estimates of 50 percent reduction by 1998 and 85 percent reduction by 2003 are conservative, based on evidence for other crops. Most of the pest problems in "other" crops will be similar to those in listed crops.

[g] These figures are derived from the methyl bromide use survey (Annex 4.1.1) in the soils chapter of MBTOC report. The total methyl bromide use reported in this survey accounts for approximately 89 percent of annual worldwide consumption of methyl bromide in soil fumigation (Table 2.3).

[h] According to industry estimates, a total of 57,407 t of methyl bromide was used for soil fumigation. The figure of 50,913 t used in this table is derived from the methyl bromide (Annex 4.1.1) in the soils chapter of the MBTOC report.

Opinion submitted by J. W. Wells

Over the many months, we have explored the technical options for the uses of methyl bromide on soils. From these deliberations, we have produced a report which considers alternatives from a qualitative rather than a quantitative point of view. Obviously, we cannot derive a quantitative percent reduction from the substance of the soils report, so we must consider this section of the executive summary a new exercise rather than a conclusion or summarisation of our work to date.

I assume that the parameters of the question posed (we have ten years, clean nursery material, and unlimited research funds) are intended to focus attention on the fact that the answer is to be strictly in terms of technical possibilities. There are, of course, additional, non-technical considerations which should be discussed in order to put any use reduction figure in context.

The economics of crop production, as well as the cost of research, must be factored into the equation. Are we going to be producing the same variety of crops and approximating the same yields? Methyl bromide soil fumigation occurs in at least 150 crops in California alone. For a number of these crops, complete replacement of methyl bromide with alternative chemicals or crop protection strategies would certainly be technically feasible in ten years. However, for many, use reduction would also mean crop reduction or severe dislocation of current cropping patterns.

Sheila Daar qualifies her opinion by stating that 100 percent use reduction could be achieved "for many current uses", and I agree many, but not all. You (R. Rodríguez-Kábana) have made the statement in support of 100 percent use reduction that "anything is possible", but such a statement, without context, can be misleading. The reality is that even if research could deliver new, environmentally acceptable compounds capable of replacing methyl bromide uses in ten years, the time to commercial development and regulatory approval would almost certainly exceed that period. Projecting a percent use reduction assumes that the alternatives will be on line, not in the researcher's laboratory. Therefore, this projection must take into account non-technical factors.

I cannot project with any degree of accuracy, a quantitative percent use reduction. I will rely upon the scientists and production agriculture members of our committee to do so. Frankly, I think the equation is not answerable at this point. I can only emphasise that any figure we derive must be put in a broader, practical and regulatory context or be at best, meaningless, and at worst, totally misleading to the decision-making body.

Opinion submitted by R. Rodríguez-Kábana

The chairman's opinion as stated to the subcommittee at Bordeaux - anything is possible given 10 years, clean nursery stock, and unlimited research funds - new compounds as effective as methyl bromide and environmentally acceptable can be developed. This together with existing alternatives could produce a 100% reduction in the use of methyl bromide in most areas. However, in the chairman's experience of more than 30 years within the United States agricultural research establishment, it is unrealistic to think that unlimited research funds will be available. To have unlimited funds to research everything possible would require time and the political will and decision shown by The Netherlands' government in that nation's successful methyl bromide replacement program.

If funds available for research continue as they are at present, then no more than 20 - 40% reduction in usage rate can be achieved within a ten-year period in countries with current efficient (20 g m^{-2}) use rates. A doubling or tripling of research investment from present level could result in up to 50 - 80% reduction. To attain 90 - 100 % reduction will require a world-wide effort involving investments in the order of tens of millions of U.S.A. dollars. This is achievable but again will require levels of political will, consensus, and support from methyl bromide user nations that are not currently available in most of them. In the United States the whole issue is moot since methyl bromide is scheduled to be removed within the ten-year period considered by the subcommittee in its discussion on the subject of use rate reduction.

B. Belgium

Opinion submitted by E. van Wambeke

Regarding the actual dosage rate of 90 g m^{-2}, and dealing almost exclusively with greenhouse soil, and assuming clean nursery material is available and hygienic measures are taken:

1. Without Alternatives *

a. Improvement in technology (mulching material and sealing), a methyl bromide reduction rate of 30% is believed to be achievable.

b. This improvement combined with disease monitoring and subsequent reduction of application frequency, should lead to a total reduction of 70% of the actual rate.

2. With Alternatives

Additionally, the inclusion of alternatives (except substrate culture), should lead to a total of 80% reduction.

* *Footnotes.*

a. Improved mulching shows the feasibility of 50% dosage reduction. Safety margins press to 30% dosage reduction.

b. Frequency is actually every year or every other year and practice showed that 3 or 4 years is feasible when observing conditions of clean material and hygienic measures.

c. Alternatives (existing fumigants) proved to be not reliable under Belgian conditions.

C. Japan

Opinion submitted by T. Kajiwara

The major crops considered were vegetables and specifically cucumber, melon, watermelon, pepper, strawberry, and tomato which are the most important in the country. Use rate reductions (in percent) expected in 10 years with alternatives are as follows:

1. When highly effective methods (including biological control, effective use of chloropicrin, and other materials) to control Fusarium wilt, Phytophthora rot and Verticillium wilt are developed 40%

2. When effective attenuated viruses to each strain of TMV are established and complete control methods (including use of dazomet and other chemicals) to nematodes are developed 10%

3. When herbicides which can be used safely during crop growing season are developed 10%

D. The Netherlands

Opinion submitted by J.A. van Haasteren

100% replacement of methyl bromide was attained in The Netherlands. In crops which can be grown on substrates (i.e. flowers, peppers, forestry and tobacco nurseries, strawberries, cucurbits, tomatoes) 100% replacement is possible within 5 years.

E. Israel

Opinion submitted by J. Katan

Reducing dosages of methyl bromide by combining with other methods of control. In certain cases, methyl bromide can be combined with other methods of control (chemical or nonchemical, e.g. solarisation), thus resulting in effective control while reducing dosages. When applicable, such a combination may result in a 50% reduction in methyl bromide dosage. This combination can be applied either simultaneously or in alternation. The following (Table 4.1.7) are figures with low and high range of dosage reduction which may be attainable by the year 2004 given alternatives and the conditions given in the table's footnotes.

Table 4.1.7 Dosage reduction in 10 years

	Percent dosage reduction by 2004[a,b]	
	Low range	High range
High rate fumigation (90 g m^{-2})	40	60
Low rate fumigation (20 g m^{-2})	30	40

[a] Using all available means, including nonpermeable mulches, improved application and nonchemical and chemical alternatives, alone or combined with methyl bromide at reduced dosage.

[b] Based on the use of pest-free propagation material and on the present knowledge.

E. Zimbabwe

Opinion submitted by B. Blair

When MBTOC visited Zimbabwe in July 1993, they received a hand-out from J.A. Shepherd (nematologist, Tobacco Research Board) with regard to use of methyl bromide in tobacco seedbeds. In this he has the following to say about the consequences of withdrawal of methyl bromide.

EDB plus burning of brushwood or corn cobs has given excellent results, but we are reluctant to recommend this on a wide scale because of environmental concerns. Dazomet, metham-sodium and 1,3-D + MITC are not as reliable as methyl bromide, but can be used and results will improve with further knowledge. The wider use of rootknot nematode-resistant grasses in rotations in the field and seedbeds, and also the greater use of *Meloidogyne javanica*-resistant tobacco cultivars will lessen the necessity for perfect control of nematodes in the seedbeds, though the problems of disease, weed and insect control will remain. The effective use of the fungus *Trichoderma harzianum* to control *Rhizoctonia solani* and *Fusarium solani* in seedbeds is dependent on reducing competing fungi; this is most easily done with methyl bromide fumigation. Though withdrawal of methyl bromide would be very disruptive, we believe that many of the problems can be overcome with time.

In my opinion, we could immediately reduce usage of methyl bromide by about 30% (presently recommended at 50 g/m^2 under a 150 µm thick polythene sheet for 48 hours) by using less permeable sheets. With the reasons given above, it is possible that there could be up to 100% reduction in methyl bromide use after about 10 years; this does not take into account increased costs. From our work on dazomet (past and recent), we are now thinking of a combination treatment with EDB to give us the spectrum of control required (EDB use is presently permitted in Zimbabwe, as it does not contaminate groundwater there).

Taking my points above into account, and those that were expressed in Bordeaux, I would suggest that the low range could be 10 - 30% (in next 5 years), and the high range could be 50 - 100% (> 5 years).

4.2 Alternatives for treatment of durables

Executive Summary

Durable commodities are commodities of low moisture content which, typically, are stable in storage over long periods. Durable commodities currently treated with methyl bromide include a wide variety of dry foodstuffs; principally cereal grains, oilseeds and legumes, grain products, dried fruit and nuts; timber and timber-containing products; and various artefacts. Insect and mite pests can breed on these materials during storage. Pests may also be present at time of harvest, and persist in storage or during transportation.

Control of pests infesting durables is essential to keep commodity losses to a minimum, to maintain quality and prevent damage, and prevent the spread of pests between countries. Fumigation is a very effective method of controlling pests. Methyl bromide and phosphine are the two fumigants which are currently used for this. Methyl bromide is able to provide rapid and complete control of pests, mostly within 24 hours of exposure, at a minimum temperature of 5°C. There are no reports of development of pest resistance in over 60 years of its use. Methyl bromide is usually the fumigant of choice for quarantine treatments, particularly against khapra beetle and wood-destroying insects.

It is estimated that approximately 13% of the annual world non-feedstock usage (1992) of methyl bromide is for the disinfestation of durable commodities. Some economically important industries have adopted methyl bromide fumigation as their principal means of pest control. These include the dried fruit and nut industry (1990 - 93 yearly average value in excess of $US 10 billion), export/import trade in unsawn timber and storage of bagged food grain stocks in some countries. Additionally, some countries fumigate substantial quantities of grain with methyl bromide on import or export to meet phytosanitary requirements (e.g. Japan, 14.6 Mt in 1992).

There are existing or potential alternatives for most uses of methyl bromide on durable commodities. However, there are no direct in-kind replacements for methyl bromide and all alternatives require some changes in practice. Although there are several potential alternatives, only phosphine is extensively in use, principally for cereals and legumes. There are technical barriers to extend its use further. Insect resistance is an emerging problem with this fumigant, particularly in developing countries. Phosphine requires a long exposure period (5 - 15 days) and usually temperatures >15°C, for effective action. With further investigation, it may be possible to extend the use of phosphine into some other areas where methyl bromide is currently used, but complete substitution by phosphine is very unlikely. For example, methyl bromide is currently used to control phosphine-resistant insects.

There are several other fumigants which may have some restricted potential as alternatives for methyl bromide. Hydrogen cyanide was widely used at one time for treatment of durable commodities, but was superseded by methyl bromide because it was both safer and more efficacious. Registration has lapsed in most countries. Ethyl formate is in use in some countries for disinfestation of packed dried fruit. Carbon bisulphide was once widely used but has been discontinued in most countries. Ethylene oxide as a fumigant for food has been withdrawn in most countries because of the production of carcinogenic residues.

Controlled and modified atmospheres provide a potential alternative to conventional fumigation if time (2 - 6 weeks) and temperature (30 - 10°C) permit. This technique is most likely to be used selectively in countries with warmer climates. The capital cost to implement a controlled or modified atmosphere disinfestation treatment in addition to the operational costs in some cases will render this alternative unviable.

Two potential new fumigants for durables are carbonyl sulphide and methyl isothiocyanate. As sufficient data are not available, neither compound is registered as a fumigant. However, registration and re-registration of any chemical compound as a fumigant is likely to be a very costly exercise because of the need to obtain extensive efficacy and toxicity data, and will also require a minimum of 5 years to complete the process.

Contact insecticides are used extensively in certain situations to protect raw durable commodities. Contact insecticides include synthetic chemicals, inert dusts, insect growth regulators and plant extracts or their analogues. Various compounds are selectively effective in controlling different insect species. One of the main constraints associated with contact insecticides is chemical residues in treated commodities. This normally prevents their use on processed products. Resistance is also a major problem. Although many of these are registered for use on durable commodities, the high cost of registration is a constraint to develop new products.

Physical methods of insect control, including cold, heat and irradiation treatments, offer further potential as non-chemical alternatives, although difficulties exist in the practical implementation of these methods.

Biological methods of insect control, including the use of pheromone and microbiological control agents are at an early stage of investigation. Their widespread use as control measures are not expected in the near future.

Developing countries may have difficulties in the transfer of technologies to reduce or replace the use of methyl bromide. To introduce technology for the use of new treatments may be both time consuming and costly. Other issues include the maintenance and servicing of complex equipment.

Introduction of better sealing techniques to improve fumigant retention should permit the lowering of dosage rates and subsequent emission of gas to the atmosphere. The use of methyl bromide and insecticides in durables can be reduced substantially by the introduction of Integrated Pest Management (IPM) systems. This will require improvements in design of storage structures. Proper training will be required to successfully introduce such an IPM system, and will require consistent maintenance in order to succeed.

Research priorities for replacement of methyl bromide include:

- development of physical control methods that are rapid and have little or no effect on the commodities;
- further development of IPM strategies;
- prompt evaluation of new fumigants and other alternatives, coupled with speedy registration procedures to enable early adoption;
- development of methods to reduce emissions from methyl bromide fumigations, including recovery and/or recycling techniques.

4.2.1 Introduction

Durables are commodities with a low moisture content that, in the absence of pest attack, can be stored easily for long periods. Most durable commodities currently treated with MeBr are foodstuffs that are stored post-harvest, before being consumed, processed or transported in or out of a country between harvests, and sometimes for even longer periods. Pest control in durables is usually to prevent damage to the commodity. Many pests can survive and proliferate on durables in storage. The risk of introducing and spreading infestation, either of field pests on the commodity or storage pests during the usual movement of commodities in trade, is a major reason for treatment of durables.

Generally, the commodities classified as durables have less than 15% moisture content. They include:

- Artefacts, including bamboo ware, museum and cultural artefacts
- Beverage crops, including cocoa, coffee and tea
- Cereal grains, e.g. wheat, rye, barley, rice, sorghum, maize
- Dried fish, meat and derived meals
- Dried fruit and nuts
- Grain products, including flour, noodles, semolina
- Herbs and spices
- Pulses, including peas, beans and lentils
- Seeds, for planting
- Tobacco (post-harvest)
- Unsawn timber and timber products

Fumigation is the principal means, globally, of disinfesting durable commodities in trade and in storage. The technique has been in use for many years. Methyl bromide is one of the most widely used of a diminishing range of fumigants available (Banks, 1994). To the knowledge of this Committee, there are no uses of methyl bromide for durable commodities without existing or potential alternatives. However, there are a number of constraints which must be considered. These are discussed below.

4.2.2 Existing uses of methyl bromide

Methyl bromide has been in widespread use as a fumigant for foodstuffs and other stored products for more than fifty years. As a result of its high toxicity to insects, exceptionally good powers of penetration and superior handling characteristics, it largely replaced hydrogen cyanide and ethylene oxide in many types of application. In addition, it has been successfully utilised in the treatment of products in circumstances which were considered at one time not suited for fumigation.

Currently, of the estimated 9855 t of methyl bromide used on durables (MBTOC estimates, Table 3.1), it is estimated that 4782 t (49%) are used on unsawn timber (logs), 472 t (5%) on dried fruit and nuts, and the remainder 4601 t (47%) used mainly on cereal grain and legumes with minor uses on other commodities, as listed above. In the absence of better figures, estimates of dried fruit and nut usage were based on the assumption that the 1991 use of methyl bromide in the state of California, USA of 189 t was 40% of 1992 global usage.

Methyl bromide has a rapid action on pests, with treatments of durables completed in a few days and, in many cases, less than 24h. The treatment time includes both the actual exposure period to the fumigant, and also times at the start when the fumigant is distributed or disperses through the enclosure and, at the end of the exposure, when residual gas is aired off. This speed of action makes methyl bromide fumigation a particularly convenient treatment where the commodity cannot be held for long periods for logistic reasons, such as at ports during import and export.

Methyl bromide is supplied as a liquid under pressure in steel cylinders and cans of various capacities. During application, liquid methyl bromide should not come into direct contact with the commodity, and especially with food materials, as taint, damage and excessive residues may result. Thus, some form of vaporisation is required. Although several devices have been developed for this purpose, typically, a coil of copper tubing immersed in hot water is used as a vaporiser for dosing a large amount of methyl bromide, particularly in temperate climates. The liquid methyl bromide is run through the coil prior to introduction into the fumigation enclosure.

For some applications, the liquid is atomised by forcing it through spray nozzles, causing rapid vaporisation by absorbing heat from the atmosphere. When using disposable cans for small scale fumigation, the fumigant is normally delivered under its own pressure by a special puncturing applicator connected to a length of flexible tubing.

There are several manuals describing techniques for treatment of durables with methyl bromide (e.g. Bond, 1984; Anon., 1989).

Methyl bromide can be regarded as one of the tools used to disinfest and protect durables from damage by pests. There are a wide variety of other measures and a large number of publications which review and describe these measures as part of an integrated system of pest control. Most of these apply particularly to cereal grain storage, but the principles are applicable to the protection of durables in general. These publications include Moulton (1988, textbook on storage of grain, pulses and oilseeds), Sauer (1992, textbook on grain storage), Bond (1984, textbook on fumigation), Snelson (1987, review on insecticide use on grain), Jayas *et al.*, (1994, reviews on techniques of pest control in stored grain) and Highley *et al.*, (1994, conference proceedings on advances in stored product protection).

In general, methyl bromide plays a small, but significant, role in the overall disinfestation and protection of durables. However, its rapid action and reliability have led to its continued use, as the treatment of choice or as a mandatory treatment, in several important situations. These are:

- treatment of unsawn logs, traded internationally, against insect pests and some fungi;
- disinfestation of bulk grain to phytosanitary or quarantine requirements at point of import or export;
- quarantine treatments against specific pests, particularly khapra beetle, *Trogoderma granarium*, and the house longhorn beetle, *Hylotrupes bajulus*;
- disinfestation of stacks of bagged grain, particularly in Africa and Singapore, and including food aid grain at point of import;
- protection and disinfestation of dried vine fruit, and of nuts in storage and prior to sale;
- disinfestation of museum objects and cultural relics.

In all these cases, though there may be alternative approaches, methyl bromide has a history of successful use. Hitherto, there has been no reason to change to less well tried measures, or ones which may involve significant changes to established practice.

4.2.2.1 Target pests

Most of the target pests of durables that are treated with methyl bromide are insects and, to a lesser extent, mites. Fungi and nematodes are not typically target organisms, except with unsawn timber and seeds for planting, respectively. Methyl bromide is sometimes specified for quarantine purposes for control of other organisms (e.g. ticks, snails) that may become entrained in durable foodstuffs or timber, but which do not normally infest and damage the commodity.

Target pests are listed in the individual sections below.

4.2.2.2 Types of fumigation enclosure

For safety and efficient action, it is necessary to enclose the commodity to be treated with some form of system, the fumigation enclosure, which restricts loss of gas to a low level.

The most efficient method of fumigating bagged or cased commodities is in chambers equipped for applying the fumigant in a manner that will ensure its rapid and even distribution, typically, a recirculation system of some type (Bond, 1984). Fumigation of commodities is also carried out:

- under gas-proof sheets of various thicknesses
- in warehouses
- in specially sealed transportable plastic enclosures ('bubbles')
- in freight containers
- in silos
- in railway box-cars
- in barges and ships
- in specially designed and equipped vacuum chambers

Many of these applications require some form of recirculation of the atmosphere within the treated enclosure in order to achieve good and rapid distribution of the added fumigant.

4.2.3 General description of alternatives

There are a large number, and variety, of potential alternatives to methyl bromide for disinfestation of durable commodities. The optimum choice of alternative is very dependent on the particular commodity to be treated and the situation in which the treatment is to be carried out. A general description of the 20 alternatives noted by MBTOC is given below, followed by a description of the alternatives as applicable to particular commodity groups.

4.2.3.1 Fumigants and other gases

4.2.3.1.1. Phosphine

Phosphine is the only fumigant, other than MeBr, which is widely registered and permitted for disinfestation of most durable commodities. It ranks as one of the most toxic fumigants known, but is used at low concentrations. Its action against pests tends to be much slower than methyl bromide, with long exposures required, particularly under low prevailing temperatures.

Phosphine penetrates well into commodities and can be removed rapidly by aeration after treatment. It has a low degree of sorption by most commodities and normal fumigation practice ensures that the residues produced are well below 0.01 g t^{-1}, the current Codex Alimentarius limit for processed cereals.

Phosphine will form an explosive mixture with air when the concentration exceeds 1.8% by volume, but this level would not be reached in normal fumigation practice. This limit reduces at reduced pressure and care needs to be taken in designing recirculation and vacuum systems using phosphine to ensure the limit is not exceeded (Green *et al.*, 1984).

Phosphine reacts with copper, silver and gold, especially in humid atmospheres, and in some situations this may preclude its use, e.g. detrimental effects on electrical equipment and machinery.

The use of phosphine can be restricted by four other important factors:

- the commodity temperature should be more than 10°C, preferably more than 15°C;
- the exposure period often needs to be prolonged for effective action against all developmental stages of pests, typically 5 to 15 days, depending on the temperature;
- proven and well controlled techniques must be used to avoid the development of resistance;
- very dry grain (<10% moisture content) may be difficult to fumigate because of restricted evolution of phosphine from the solid metal phosphide formulations that are normally used.

The toxicity of phosphine to arthropod pests is well researched and dosage schedules are available for the common stored product insects and mites (Annex 4.2.1).

The period of exposure has a much more important role than concentration levels in the toxicity of phosphine. The use of *ct*-products as a measure of dosage for phosphine is not valid unless the exposure period over which it applies is stated. All stages in the life cycle of stored-product insects have a broadly similar tolerance to methyl bromide (a factor of 3x or so). However, there is a high degree of variation in tolerance to phosphine, with eggs and pupae being much more tolerant than larvae and adults. Mites are difficult to control with phosphine since the egg stage is highly tolerant.

Resistance is an immediate, practical problem and high levels are known to occur in several species of stored-product beetle pest (Taylor 1989; Price and Mills, 1988). High levels of resistance have been measured in laboratory tests on field strains collected in several countries, particularly from parts of Africa and the Indian subcontinent, resulting from frequent use of the fumigant in conditions of poor gastightness. There have also been control failures attributable to this resistance. Resistance to phosphine is manageable provided that the necessary gas concentration can be maintained for the longer exposure periods required by more tolerant strains. In leaky situations such as silos, insect control may be carried out by a continuous input of fumigant using a phosphine-carbon dioxide mixture from a pressurised cylinder (Winks, 1990). However, for preference, the degree of gastightness of the enclosure can be improved, e.g. as described for enclosures around stacks of bagged grain in Anon., (1989), so that gas may be retained for a sufficient period. Multiple dosing may also assist.

There are many publications describing application of phosphine to stored grain and other durable commodities (e.g. Bond, 1984; Banks, 1986).

Various proprietary formulations of phosphine are available world wide. Most contain aluminium phosphide or, less commonly, magnesium phosphide, formulated with ammonium carbamate or urea to lessen the risk of flammability. Phosphine is generated *in situ* by the reaction of atmospheric moisture with the metallic phosphide (Bond, 1984). There is also limited availability of phosphine in pressurised gas cylinders as a non-flammable 2% mixture in carbon dioxide, as currently utilised commercially in the SIROFLO® process (Winks, 1989).

4.2.3.1.2. Hydrogen cyanide

Hydrogen cyanide was previously widely used as a fumigant for durable commodities. It has been largely superseded by methyl bromide and phosphine, both of which are much more convenient and, in many cases, more effective to use. Modern instructions for use of HCN are given in Anon., (1989). These relate particularly to the ASEAN region, but are, in principle, suitable for most tropical countries.

Hydrogen cyanide availability and registration or re-registration difficulties may prevent immediate substitution of the gas for particular uses of methyl bromide should these be required. Cylinders of liquid hydrogen cyanide are unstable and cannot be stored for long periods. However, hydrogen cyanide can be developed *in situ* from sodium cyanide (Anon., 1989). It is the fumigant of choice, where permitted, against rodents because of its very rapid action. The Codex Alimentarius approved residue limits for hydrogen cyanide residues in grain and flour have recently lapsed, due to lack of support.

4.2.3.1.3. Ethyl formate

Ethyl formate was formerly used as a fumigant for grain. Its use is now restricted to use on dried fruit and processed cereal products, where permitted.

The action of ethyl formate against pests of durable foodstuffs is quite rapid with optimum exposures of a few hours only, but problems of distribution of this highly sorbed fumigant usually leads to the need for exposures of several days. Typical dosages on dried vine fruits are 3 to 6 mL per 15 kg, with action complete within 24h.

4.2.3.1.4. Carbon bisulphide

Carbon bisulphide was formally widely used as a fumigant for bulk and bagged grain, where it was typically applied as a 'liquid fumigant' in a mixture with carbon tetrachloride or on its own. In most countries its use has been discontinued and registration has lapsed. However, it is still used in parts of Australia, where it is applied to farm-stored grain (typical quantities treated are 50 tonnes). Application to large bulks is restricted by the potential fire hazard of the material and safe methods for large scale use need to be developed.

4.2.3.1.5. Carbonyl sulphide

This is a gas with insecticidal properties (Banks and Desmarchelier, 1993), but its use as a fumigant is not currently registered. Its use as a potential replacement for methyl bromide has recently been patented. However, field evaluations and residue studies are not yet available. It has good penetration properties with activity against most stored grain pests at about 200 - 600 g h m^{-3} at 25°C (Desmarchelier, 1994). Development of carbonyl sulphide as a fumigant for durables, including timber, is being actively pursued.

4.2.3.1.6. Ozone

Apart from the sterilising action of ozone against bacteria and viruses, only limited information is known about its toxicity to insects and to stored product pests in particular. It shows some potential as a fumigant, but will require the normal regulatory approval process to be acceptable for use, if found technically useful.

Activity has been found against *Sitophilus oryzae* and *Oryzaephilus surinamensis* (Yoshida, 1975), *Tribolium* spp. (Erdman, 1979) and *Ephestia elutella* (Mills, 1992).

4.2.3.1.7. Methyl isothiocyanate (MITC)

MITC was introduced in 1959 by Schering AG as a soil nematicide under the trade name Trapex. It kills nematodes, certain soil fungi, soil insects and also has herbicidal qualities.

This compound is being studied as a grain fumigant and protectant (Ducom, 1994). Preliminary studies of biological efficiency show that MITC is very active against *Sitophilus granarius* (all stages) at a very low *ct*-product of 8 g h m^{-3}. For optimal results, this compound has to be very well mixed with the grain.

4.2.3.1.8. Sulphuryl fluoride

This compound has been developed as an effective fumigant, mainly for termite control. It is applied to residences or other buildings which are covered with gas-proof sheets. It is very toxic to all post-embryonic stages of insects (Kenaga, 1957; Bond and Monro, 1961), but the eggs of many species are very tolerant. In laboratory and field tests, sulphuryl fluoride produces no objectionable colour, odour or corrosive reactions to photographic supplies, metals, paper, leather, rubbers, plastics, clothes or many other articles fumigated (Gray, 1960). Methyl bromide affects several of these materials adversely.

Guidelines for use, from the sole U.S.A. producer, specifically state (Dow Chemical Company, 1963) that: "under no conditions should sulphuryl fluoride be used on raw agricultural food commodities, or on foods, feed or medicinal products destined for human or animal consumption or on living plants", as the product is not currently registered on foodstuffs.

4.2.3.1.9. Ethylene oxide

Ethylene oxide was used extensively for many years to reduce microbial contamination spoilage and in food commodities such as spices, cocoa beans and some processed foods and was also used for insect control on grain (Cartox system). From 1980, its use was withdrawn within the European Community but it is still used in many other parts of the world.

Because of its flammability, ethylene oxide is generally supplied in mixtures with inert diluents such as CO_2 or HCFCs. Ethylene oxide reacts with chemical constituents of some food commodities producing potentially carcinogenic compounds. The detection of the reaction product, ethylene chlorohydrin, was reported by Wesley *et al*., (1965) and ethylene bromohydrin was found in flour and wheat previously treated with MeBr followed by ethylene oxide (Heuser and Scudmore, 1969).

Where health and environmental regulations permit, ethylene oxide may potentially replace MeBr in some non-food uses, notably treatment of some artefacts, manuscripts and other archive and museum materials. However, other approaches such as freezing or inert atmospheres may be found more appropriate (see Section 4.2.9).

4.2.3.1.10. Controlled and modified atmospheres

Treatment with controlled or modified atmospheres based on carbon dioxide and nitrogen offers alternatives to fumigations with toxic gases for insect pest control in all durable commodities. They are ineffective against fungal pests.

Low oxygen atmospheres, typically created by adding nitrogen to a fumigation enclosure, require that there be a maximum of 1% oxygen for effective action. Carbon dioxide atmospheres typically are applied at about 60% CO_2 in air. At this level there is about 8% oxygen present, normally enough to support most stored product pests indefinitely. CO_2 thus is regarded as having a toxic effect on insect pests (Jay 1971) and not to act just as an inert gas that reduces the oxygen level to below that supporting life.

The effective use of CO_2, for grain storage, was developed principally in Australia and the USA, although Australia, for preference, currently uses phosphine to treat bulk grain. However, the knowledge gained is being used for stored rice and other bagged commodities in some ASEAN countries (Nataredja and Hodges, 1990). Until recently, use of CO_2-based atmospheres were preferred over nitrogen-based ones for bulk grain for various technical reasons. Recent developments in the on-site generation of nitrogen-based atmospheres have made these atmospheres more competitive in price and convenience (Banks *et al*., 1991). Nitrogen-based controlled atmospheres are in commercial use in Australia in an export grain terminal in bins originally designed and equipped for methyl bromide treatments (Cassells *et al*., 1994).

Data on exposure times for control are available for many species and stages of stored product pests under particular sets of conditions (Annis, 1986; Bell and Armitage, 1992). Most species are completely controlled by exposures of 2 - 3 weeks at 25 - 30°C. As an extreme case, larvae of *T. granarium* in diapause require exposures longer than 17 days at 30°C or less, with CO_2 levels at or above 60% in air (Spratt *et al.*, 1985).

Structures for use with controlled or modified atmospheres must be well sealed, if high rates of gas usage and expense are to be avoided. The sealing level specified for methyl bromide use in silos in Japan (see Section 3.5.2) is also suitable for either CO_2- or nitrogen-based CA systems.

Use of controlled or modified atmospheres may require registration or other regulatory approval in some countries.

4.2.3.2 Contact insecticides

Unlike fumigants, contact insecticides may provide persistent protection against reinfestation. These chemicals can be applied either directly to grain for protection against insect pests, or to storage buildings and to transport vehicles in order to reduce the likelihood of cross-infestation or re-infestation of commodities. They are not normally registered for use on processed commodities.

Generally, fumigants, such as methyl bromide, have a somewhat different action on pests and role in stored product protection to contact insecticides. Differences, when used on stored grain, are summarised in Table 4.2.1. Despite these differences, where permitted by market preference and regulatory authorities, both techniques can result in pest-free end product.

Table 4.2.1 The basic differences between contact insecticides and fumigants are:

Fumigants	**Contact insecticides**
No lasting protection	Lasting protection possible
Grain can be treated *in situ*	Normally grain has to be moved in order to apply insecticide
Can be used for treating most commodities	In most countries, only permitted on commodities before processing
Disinfestation can be completed within 1-15 days, according to temperature	Disinfestation achieved over a longer period since stages of those species which develop within the grain are not affected until they develop into adults
Skilled, certified personnel only can apply fumigants	Semi-skilled operators can apply contact insecticides
Effective generally against all insect species	Various compounds are selectively effective against different insect species
No incidence of substantial methyl bromide tolerance known, but development of resistance to phosphine a current concern	Most insect pests develop resistance to particular insecticides or groups of insecticides, with continued use
Good penetration of grain bulks	Poor penetration of grain bulks

4.2.3.2.1. Organophosphorus compounds

This is an important group of grain protectants in current use. The stability of deposits on grain vary widely with particular material and ambient conditions. The rate of degradation increases both with temperature and water activity (moisture content). Furthermore, toxicity to insects increases with temperature. In consequence, persistence of the biological effectiveness will depend upon the insecticide used. For example, typically dichlorvos becomes ineffective within several days, while malathion takes several weeks, and pyrimiphos methyl many months.

Most are poorly effective against bostrichids (*Rhyzopertha dominica* and *Prostephanus truncatus*).

The principal materials used world-wide include: chlorpyrifos methyl, dichlorvos, fenitrothion, malathion, and pyrimiphos methyl. Registrations vary between different countries.

4.2.3.2.2. Synthetic pyrethroids

Synthetic pyrethroids are a group of insecticides with chemical constitution based on that of the active ingredients of natural pyrethrum. Deposits are quite stable on grain and their insecticidal activities may persist up to 2 years (Snelson, 1987). Their action is much less sensitive to temperature than organophosphorus insecticides. Pyrethroids are active against bostrichid beetles at a much lower dosage than for most other insect pests of durables. Most pyrethroids are of low acute toxicity to human beings. A disadvantage of these pesticides is their relatively high cost. In many situations pyrethroids are added in combination with a synergist, piperonyl butoxide, to increase effectiveness and reduce cost.

4.2.3.2.3. Botanicals

These compounds are derived from plants. At present, the only botanical in widespread use in developed countries for protection of durables (grain) is pyrethrum extract. Others, such as azadirachtin, are under active investigation. A wide variety of botanicals are still used by subsistance farmers in developing countries.

Botanicals, as natural products, are not readily patented and there is little incentive for companies, and other organisations, to pay for the toxicological testing required to gain registration for use.

4.2.3.2.4. Insect growth regulators (IGRs)

The term insect growth regulator (IGR) is used to describe compounds which interfere with the life-cycle of pests. They are not normally directly toxic to adult pests.

IGRs are considered to be more pest-specific than conventional contact insecticides. One potential disadvantage of IGRs is their long persistence on foodstuffs. This may limit their use in some potential applications. The earliest of the IGRs developed were analogues of juvenile hormones, and include methoprene and hydroprene.

Some IGRs act against insects via ingestion and/or contact (e.g. methoprene), whilst others act only via ingestion (e.g. diflubenzuron). They tend to have low toxicity to vertebrates (Menn *et al.*, 1989) and thus to have a substantial margin of safety when used. The major disadvantages of IGRs are the high cost and inability to control adult stages.

Methoprene has been registered for use in the protection of a variety of stored agricultural commodities in a number of countries including the USA, Australia and the UK. It is effective against many stored product pests, including *L. serricorne*, *E. cautella*, *P. interpunctella*, *T. granarium*, *R. dominica* and *O. surinamensis*, but not against *Sitophilus* spp. (Snelson, 1987; Mkhize 1986).

Diflubenzuron and fenoxycarb have also been evaluated as a grain protectant but is not yet registered (Samson *et al.*, 1990).

4.2.3.2.5. Inert dusts

Various of these inert dusts are registered in some countries for treatment of grain and grain legumes against insect pests. They are particularly useful in dry conditions as a means of controlling pests resident in storage structures. They lose effectiveness at high relative humidity, greater than about 75% r.h. (Le Patourel, 1986). Inert dusts may be useful as part of an integrated system that controls pests to a level where methyl bromide use is not required. Their use on durables, particularly grain, has recently been reviewed (Banks and Fields, 1994).

Inert dusts, such as those based on diatomaceous earth (e.g. Dryacide® (Desmarchelier and Dines, 1987)), can provide effective pest control in dry grain. However, though direct admixture can give long term (some years) protection from infestation and thus avoid need for fumigation, dusts have adverse effects on the handling qualities of grain and can cause excessive wear in handling machinery. These factors tend to prevent their use in many large-scale storage facilities. They have some particular use as admixtures in seed storage and in small-scale, farmer stores for animal feed.

Inert dusts, such as Dryacide, find particular application as prophylactic sprays to control insect pests in grain storage structures as part of an integrated control program. They are widely used for this purpose in Australia.

There are four basic types of inert dusts:

- Clays, sands and earths. These traditional materials are used as a protective layer on top of stored seed.
- Diatomaceous earth is the fossilised remains of diatoms, microscopic unicellular aquatic plants that have a fine shell made of amorphous hydrated silica. It consists mainly of silica with small amounts of other minerals. Proprietary insecticidal formulations are available. The dusts are effective against a wide range of pests when admixed to grain even at rates of 1 kg t^{-1} or less.
- Silica aerogels are very light, non-hydroscopic powders effective at slightly lower doses than diatomaceous earth formulations.
- Non-silica dusts, such as phosphate and lime. Phosphate has been used in traditional stores in Egypt (Fam, 1974).

Inert dusts such as ash and lime have a long history of use for grain protection (Ebeling, 1971; Golob and Webley, 1980; Ross, 1981; Quarles, 1992a,b). Dryacide, an activated diatomaceous earth, is in widespread use in Australia in the grain handling industry (including rice) using slurry application for structural spray as a prophylactic treatment against storage pests. There is limited use in Australia as a direct admixture for preserving stock feed and seed for planting.

Inert dusts can be quite rapid in their lethal action under favourable conditions, with complete mortality of adult insect pests can be achieved within 7 days at low dosage rates.

Available data on responses of immature stages of grain pests is limited, although the success of inert dusts in suppressing population growth suggests that they are likely to have a strong effect on free living immature stages. It is not necessary for insects to be completely covered with the inert dust for it to be active (Maceljski & Korunic, 1971).

Some inert dusts are accepted as 'organic'. Diatomaceous earths are widely used as food and processing additives. There are no obvious environmental hazards, but there are concerns about worker exposure to uncontrolled dust levels.

The main advantages of inert dusts are that they do not require capital equipment, are relatively non-toxic, provide continued protection, and do not affect baking quality (Desmarchelier and Dines, 1987; Aldryhim, 1990). The main disadvantages are decreased flowability of grain, visible residues that can affect grading, and decrease the bulk density of grain. They can also give rise to dust problems in the workspace. To alleviate the dust problem, inert dusts can be applied as an aqueous slurry for surface treatments, as in Australia, although this can reduce effectiveness somewhat (Maceljski and Korunic, 1971).

4.2.3.3 Physical control methods

4.2.3.3.1 Cold treatments

In general, cold treatments are not used specifically for disinfestation of large batches of durables, though they may be useful in specific instances, such as small museum objects or small quantities of cereals where a mild non-chemical disinfestation is required. Under these circumstances, they can present an alternative to methyl bromide use.

For rapid action, a few days exposure, very low temperatures are needed to ensure disinfestation (-15°C or below). The rate of cooling to this temperature must be rapid to avoid acclimation (Chauvin and Vannier, 1991; Fields, 1992).

Below about 10°C reproduction ceases and infestation of populations of most pests of durables slowly decline. Evan at 4°C adults of most species survive for many months, though their immature stages may be killed. Species of tropical origin such as *Sitophilus oryzae*, *S. zeamais*, *Tenebroides mauritanicus* and *Lasioderma serricorne* tend to be cold sensitive, whereas some important pests including *Cryptolestes* spp., bruchids, mites and some Lepidoptera are very tolerant (Armitage, 1987; Lasseran and Fleurat Lessard, 1991; Fields, 1992). In consequence, cooling typically is used to prevent damage and multiplication and reinvasion of pests rather than as a disinfestant.

4.2.3.3.2 Heat treatment

Heat treatment technologies are notable as one of the very few pest control options for durables which are capable of matching the speed of treatment afforded by methyl bromide and other fast-acting fumigants. Commodities need to be heated to temperatures of 50 to 70°C and then rapidly cooled to avoid damage to heat-sensitive products. The time required is strongly dependent on the temperature reached and experienced by the target pest. Disinfestation from stored product pest insects (all stages) can be achieved in less than one minute at about 65°C.

Fluid-bed heating systems for bulk grain have been developed to a commercial prototype stage, with treatment rates of up to 150 t h^{-1} (Evans *et al.*, 1983; Thorpe *et al.*, 1984; Fleurat-Lessard, 1985). Pilot studies have been carried out on the use of rapid heating of grain by microwaves or radio frequency radiation for the disinfestation of grain (Nelson, 1972; Fleurat-Lessard, 1987). Installation of large scale heat treatment facilities is likely to be capital intensive.

4.2.3.3.3 Irradiation

Irradiation is a potential method of controlling pests in or on a wide variety of durable commodities. It is already in use commercially in some situations. The process involves the use of gamma energy, accelerated electrons or X-rays to penetrate the commodity. The effectiveness of treatment for insect control and effects on food quality, is related to the energy delivered.

Disinfestation by irradiation has a long history (since 1912) and a sizeable research investment. Brower and Tilton (1985) and Tilton and Brower (1987) summarised the radio-sensitivity data on forty stored-product pest species, discussed the possible use of irradiation as a quarantine measure for these species, and discussed irradiation disinfestation of grain and grain products. These data showed that pests vary in their sensitivity to radiation. Generally, the developmental stages are more sensitive than adults; females are more sensitive than males and adults are more easily sterilised than killed. As a group, the beetles are more sensitive than moths, and fruit flies are more sensitive than beetles. Mites have a range of sensitivity similar to that of beetles.

The International Consultative Group on Food Irradiation (ICGFI), under the aegis of the FAO/IAEA Joint Division, has published a provisional guideline for the irradiation of cereal grains for insect disinfestation as a recommendation to be followed when using the technology (ICGFI, 1988).

Selection of the type of irradiation equipment to be used depends on whether the commodity is to be irradiated in packages or in bulk, the quantity of product to be treated and other factors. Gamma irradiators can treat packaged or bulk products; and accelerators can more effectively treat bulk products in thin layers (2-5cm thickness).

There are few agreements presently that allow movement of irradiated products in international trade. This is an impediment to the more widespread use of the method and is especially critical when the irradiation is used to satisfy quarantine requirements. The food industry is concerned about consumer acceptance of irradiated food products. There are also questions regarding the large initial capital expenditure required for plant construction and related logistics (Rhodes, 1986).

Disinfestation of grain, oilseeds, legumes and other dry stored products by irradiation is an effective technique that may satisfy quarantine needs in particular situations. However, there are no approved quarantine treatments to date.

4.2.3.3.4 Physical removal (sanitation)

Sanitation forms an important part of any normal management of durables in storage. It aims to reduce the need for pest control, including reducing frequency of, or eliminating the need for fumigation of methyl bromide, if practised. Sanitation is, in general, the application of a diverse range of measures designed to remove pests or prevent their access to the product or commodity. These include cleaning and removal of harbourages for pests, including removal of food residues in which pests can multiply, and reengineering machinery and buildings. Normal good warehousing practice, e.g. stock rotation and, where applicable, insect proof packaging, are also part of sanitation, as both measures reduce pest population pressure. Other measures include application of insecticidal sprays to control pest movement into the stored commodity.

Physical removal, sanitation and packaging as methods to assist pest control in stored grain has recently been reviewed (Banks and Fields, 1994).

4.2.3.4 Biological methods

Biological methods have potential to provide long-term protection for stored commodities in specific situations. Use of biological agents to control insect pests in storage situations has recently received renewed attention. Two types of biologically-based systems are considered possible:

- from insect predators and parasitoids (classical biological control)
- from microbial pathogens

These biological agents are generally host specific and considered to be primarily preventive control measures (prophylactic). They are not directly comparable with MeBr fumigation because of their specificity, except in instances where only a few target pests are prevalent (e.g. in flour mills). In some cases they have been shown to provide long term control and can be used for space treatments.

4.2.3.4.1. Biological control with predaceous insects or parasitoids

The presence of beneficial predators or parasitoids as opposed to pest species in stored products has not been addressed by many regulatory agencies. However, the US EPA recently exempted predators and parasitoids from tolerances on various stored products. Sometimes no differentiation is made by regulators or the market between predator or pest species, and any insect is considered a contaminant. Such considerations are impediments for introducing beneficial insects into stored products even if their use is strictly for control without suffering penalties in product grade.

The situation may be different with hymenopterous parasitoids of stored-product insects which are very active and which, because of their very small size, cannot be easily detected in commodities. The parasitoids live outside bulk of grains and their activity remains on the surface layer. Consequently, they are active biological control agents mainly for free living pests. The more effective species are *Bracon hebator*, a larval parasitoid (Press *et al.*, 1982; Brower and Press, 1990; Cline and Press, 1990) and *Trichogramma evanescens*, an egg parasitoid (Brower, 1988a, 1988b). The primary target pest species are flour moth larvae or eggs and various beetle larvae. *Bracon hebator* is in use currently in South Africa for reducing the need for fumigation of stacks of bagged grain (Anon., 1991).

The effectiveness of the warehouse pirate bug, *Xylocoris flavipes*, has been evaluated in regulating stored product pest populations (Brower and Mullen, 1990; Brower and Press, 1992). After introduction of large numbers of the pirate bugs in storage premises, the populations of *Tribolium castaneum* can be suppressed in a short period of time (Press *et al.*, 1975; Wen and Brower, 1994).

4.2.3.4.2. Insect pathogens as microbial control agents

Pathogens of insects include bacteria, viruses, protozoa, nematodes, and fungi. Among these, the bacteria, viruses and protozoa have been most studied for use as control agents for stored product insects. A number of baculoviruses and numerous strains of *Bacillus thuringiensis* (Bt) have been registered in some countries but few have been developed for use on durables. Bt was produced and tested commercially for durables pests as early as 1927 (Métalnikov and Métalnikov, 1935). Bt is exempt from a tolerance in the USA, but not in other countries, for use as a stored product protectant. Resistance by pests in stored products to Bt has been observed (McGaughey and Beeman, 1988).

Bt is mass-produced by fermentation processes and is highly standardised as to activity and safety of each production lot. Residual activity against susceptible insects can last for more than a year (McGaughey, 1986). Regulatory acceptance is needed by many countries for application of Bt to durables.

Entomopathogenic viruses (primarily baculoviruses) have been extensively studied for the control of field pests and to a lesser extent for postharvest pests. Approximately eight baculoviruses have been registered for use, mostly in the United States, Canada and Europe. Thus far all have been for control of agricultural or forest pests. The granulosis virus of the Indian meal moth has been the most studied for control of a stored product pest (Hunter *et al.*, 1973; McGaughey, 1982; Cowan *et al.*, 1986; Kellen and Hoffmann, 1987). More recently the process for production and formulation of the virus was patented (Vail, 1991). Other baculoviruses have been isolated from many of the important lepidopterous pests of durable commodities (Hunter and Dexel, 1970; Hunter and Hoffmann, 1972) and need to be studied further as potential control agents.

The protozoan pathogens of insects infesting durables have been studied extensively. Generally, their action is chronic, not acute. However, their usefulness for population regulation has been demonstrated (Brooks, 1971). Several have been reported to have very broad host ranges (Kellen and Lindegren, 1973). Dissemination by the use of pheromone traps has also been demonstrated (Burkholder and Boush, 1974; Shapas *et al.*, 1977). To date protozoan pathogens have not been registered for use on durable commodities. Further studies need to be conducted on the potential utility of these organisms.

4.2.3.4.3. Pheromones

Pheromones are chemicals that are released into the external environment by insects that elicit a specific reaction in a receiving individual of the same species.

There is some possibility for insect pest control by manipulation of the chemical communications which control insect behaviour (Edwards *et al.*, 1991). Some pheromone molecules have been chemically characterised and synthesised. Pheromones may be used in an insect control program in two ways: by population density surveys and direct behavioural control. Only the latter can be considered as a true control measure. It is based either on stimulation of behaviour of the pest species (used in mass trapping techniques) or on inhibition of behaviour, (particularly mating disruption) (Trematera, 1988). Pheromone monitoring systems have the potential to be used to indicate where action is required, allowing decisions to be made to avoid treatments, including methyl bromide fumigations, when pest populations are below damaging levels. As a mating disruption agent it may decrease the reproductive potential of the target species to a very low level when population density is initially low. If used as a control measure, registration may be required. The registration procedures for such control systems for stored commodities are lacking and need clarification.

4.2.4. Alternatives to methyl bromide in stored cereal grains and similar commodities

4.2.4.1 Commodities and pests

A wide variety of stored cereal grains, and grain legumes (pulses), have been treated with methyl bromide. Examples are given in Table 4.2.2. Products made from cereals and legumes, including flour, pastas, semolina and compounded animal feed, have also been treated. This category also includes similar products such as sago and cassava chips. Fumigation of wheat flour or ground legumes with MeBr is becoming less common, since odours or taint may develop in bread or other products prepared from those finely-divided commodities.

Oilseeds (e.g. sunflower seeds, soybeans) and oilseed expeller cake are also sometimes treated with methyl bromide for control of insect and mite pests. These materials absorb methyl bromide strongly and, generally, other measures are used in preference (e.g. cooling, processing).

Table 4.2.2 Examples of cereal and legume crops which may be fumigated with methyl bromide

Common name	Scientific name
Barley	*Hordeum vulgare*
Beans	*Phaeseolus* spp., *Vigna* spp.
Buckwheat	*Fagopyrum sagittatum*
Cassava	*Manihot esculenta*
Lentil	*Lens culinaris*
Maize	*Zea mais*
Millet	*Pennisetum* spp.
Oats	*Avena sativa*
Peanut	*Arachis hypogea*
Peas	*Pisum sativum*
Pigeon pea	*Cajanus* spp.
Rice	*Oryza sativa*
Rye	*Secale cerale*
Sorghum	*Sorghum bicolor*
Soybean	*Glycine max*
Wheat	*Triticum aestivum*

Table 4.2.3 Principal pests of cereals and similar commodities

Scientific name		Common name
Acanthoscelides obtectus	*	Dried bean beetle
Acarus siro		Flour mite
Callosobruchus chinensis	*	Cowpea beetle
Callosobruchus maculatus	*	Cowpea beetle
Caryedon serratus		Groundnut borer
Corcyra cephalonica		Rice moth
Cryptolestes ferrugineus		Rust-red grain beetle
Ephestia cautella		Tropical warehouse moth
Ephestia elutella		Tobacco moth
Ephestia kuehniella	*	Mediterranean flour moth
Gnatocerus cornutus		Broad horned flour beetle
Nemapogon granellus		European grain moth
Niptus hololeucus		Yellow spider beetle
Oryzaephilus surinamensis	*	Saw-toothed grain beetle
Plodia interpunctella	*	Indian meal moth
Ptinus fur		White-marked spider beetle
Ptinus tectus		Australian spider beetle
Rhyzopertha dominica	*	Lesser grain borer
Sitophilus granarius	*	Granary weevil
Sitophilus oryzae	*	Rice weevil
Sitophilus zeamais	*	Maize weevil
Sitotroga cerealella	*	Angoumois grain moth
Stegobium paniceum		Drug store beetle
Tenebrio molitor		Yellow mealworm
Tenebroides mauretanicus		Cadelle
Tribolium castaneum	*	Rust red flour beetle
Tribolium confusum	*	Confused flour beetle
Trogoderma granarium	*	Khapra beetle
Zabrotes subfasciatus		Mexican bean beetle

* Major pests

4.2.4.2 Scope of the problem

Methyl bromide is effective against all stages of stored grain pests (Thompson, 1970). The degree of susceptibility varies somewhat with developmental stage, with pupal stages of insects and the egg and hypopal stages of mites usually more tolerant. Typical pests and dosage rates required for control are given in Table 4.2.3 and Annex 4.2.3. Diapausing larvae of the khapra beetle (*Trogoderma granarium*) (Bell *et al.*, 1985) and warehouse moth (*Ephestia elutella*) (Bell, 1976) are highly tolerant of methyl bromide and dosage/exposure periods increased to control these species. The dosages also vary with the temperature (Bond, 1975) and the types of commodity being fumigated (Annex 4.2.4). Psocids (*Liposcelis* spp.) can be controlled effectively using MeBr (Pike, 1994). Although formerly used widely, methyl bromide is now restricted in developed countries largely for grain disinfestation required by quarantine and official phytosanitary regulations.

In many countries bulk grain and animal feedstuffs are stored either in silo bins or on floor storage. In both situations, infested commodities are treated with methyl bromide effectively by forced air recirculation in a completely closed system (Monro, 1956; Storey, 1967, 1971a, 1971b). Procedures employing carbon dioxide as a carrier to assist the distribution of MeBr have also been used (e.g. Calderon and Carmi, 1973).

Bagged grain, rice or legumes can be treated in fumigation chambers, containers or under gas-proof sheets.

4.2.4.3 Existing substitutes for cereal grain and similar commodities

There are a wide range of processes available for control of pests in stored bulk and bagged grain. A selection of these can be used in an IPM strategy to reduce or eliminate the need for methyl bromide treatment where this treatment is used to control infestation prior to shipment, at import or prior to sale. Most methyl bromide used on grain is used for this purpose. Alternative integrated control strategies can be used to protect grain stacks from pest damage, another major use. The alternatives given below should not be regarded solely as one-for-one substitutes for methyl bromide use, but as a set of tactics which singly, or in combination, can be used to achieve this aim.

Generally, except for specific circumstances already detailed (Section 4.2.2), methyl bromide is little used in grain protection in store and trade, as the alternative technologies already provide an effective solution.

4.2.4.3.1. Phosphine

Phosphine is widely used for treating infestation in bulk and bagged grain and grain products in many countries. Typically, aluminium phosphide preparations are added to the grain, or placed on the grain surface or near the product to be fumigated within the fumigation enclosure. These release phosphine over a period of hours or days on contact with ambient moisture vapour. This process has superceded use of methyl bromide in many parts of the world. However, methyl bromide is still used, particularly at point of import or export (e.g. into Japan) or on stacks of bagged grain (e.g. parts of Africa, Singapore). In the first case, the speed of action and recognised effectiveness against pests of quarantine significance makes methyl bromide the preferred fumigant compared to phosphine, while, in the second case, methyl bromide use has been developed into an efficient, effective and reliable system, with no apparent need to change until hitherto.

Where regulations permit, in-transit fumigation of bulk and bagged grain on board ship can replace disinfestation with methyl bromide at point of export. Shipboard in-transit fumigation with phosphine is now a well developed technology (Leesch *et al.*, 1978; Redlinger, *et al.*, 1979; Zettler, *et al.*, 1982). It requires ships of appropriate design and stringent safety precautions (Snelson and Winks, 1981; IMO, 1993). Several grain-exporting countries, including Canada and Australia, require grain to be free of infestation at point of export and thus cannot use the system. However, technically it presents a method where the slow action of phosphine does not interfere substantially with the flow of trade through export ports and thus presents a feasible alternative to rapid methyl bromide treatments ashore.

Presently, there is no approved substitute to methyl bromide for treatment of khapra beetle (*Trogoderma granarium*) to quarantine standards in grain (and most other durable commodities) (but see Table 4.2.15). Phosphine is highly effective against all stages of this noxious pest (Bell *et al.*, 1984, 1985), including the normally tolerant diapause larva, provided a sufficient exposure period can be used (5 - 10 days, depending on temperature) and the temperature is greater than 15°C (as is usual in regions where this pest occurs). Further studies are required to provide data for approval of phosphine treatments by quarantine authorities.

Recent developments in phosphine fumigation technology, including use of surface application in sealed systems and supply of non-flammable phosphine formulations in cylinders at about 2% w/w in CO_2 (Winks, 1985; Chakrabarti *et al.*, 1987; Chakrabarti, 1994) have increased the competitiveness and effectiveness of phosphine use compared with methyl bromide. Discussion of recent advances in phosphine treatment of grain against infestation can be found particularly in Navarro and Donahaye (1993) and Highley *et al.*, (1994).

4.2.4.3.2 Controlled atmospheres (CA)

CA treatments based on either nitrogen or CO_2 atmospheres provide technical alternatives to methyl bromide-based disinfestations of bulk or bagged grain provided adequate exposure periods (often more than 2 weeks) can be arranged logistically.

Controlled atmospheres require well sealed systems if they are to be effective and to avoid excessive usage of gas to maintain the required atmospheric concentrations of oxygen and or CO_2. Silo bins sealed to a standard suitable for recirculatory fumigation with methyl bromide are typically suitable for CA use. Application of CA may be constrained by the cost of the CO_2 or nitrogen required, particularly in developing countries. However, the technology of generating nitrogen from air on-site is progressing rapidly and cheap, efficient systems can be expected to be available in the near future. On-site generation of nitrogen and CA treatment has been successfully trialled in a large grain export terminal in silo bins designed for methyl bromide treatment (Cassells *et al.*, 1994). It has not yet been adopted as an alternative commercially.

Because of the slow speed of action compared with methyl bromide, CA is often not regarded as a potential substitute for its use. However, if CA is regarded as a tool in an integrated protection system it may be suitable. Under Australian conditions, where a high level of pest control is achieved prior to moving grain to the export terminal, CA systems may then be used to maintain grain pest-free there until exported. One terminal recently adopted this strategy in part of the facility converting a series of silo bins, including two equipped for methyl bromide fumigation to nitrogen-based CA use (Cassells *et al.*, 1994).

CO_2-based CA systems are used on a large scale in Indonesia for long term storage of bagged milled rice stocks (Nataredja and Hodges, 1990). This system replaced a strategy of frequent methyl bromide fumigation and appears technically suitable for this wherever bagged grain is stored in warehouses long term and CO_2 is available at reasonable cost.

4.2.4.3.3 Grain protectants

Grain protectants, typically organophosphate and pyrethroid insecticides and IGRs, do not readily penetrate bagged or bulk grain. This restricts their utility substantially as normally they must be applied to the grain during handling, e.g. prior to bagging or on to grain on conveyors or elevators. They are also used as sprays on storage structures and the surfaces of bagged or bulk grain as part of a sanitation program.

The use of grain protectants varies widely with country, market preference and local regulations. Where permitted, and where pest resistance is not a problem, they can provide a useful means of avoiding the circumstances where fumigation, including methyl bromide, may be otherwise used.

Dichlorvos is unique amongst the commonly used grain protectants in its rapid action against pests and lability on grain. In the absence of resistance and, where approved, it can be sprayed onto bulk grain within a few days of export to disinfest a cargo. Subject to an adequate withholding period for the residues to decay to acceptable levels, such a treatment can provide a direct alternative to disinfestation with methyl bromide.

While dichlorvos is currently approved under the Codex Alimentarius for application to raw cereal grains with a maximum residue level of 2 g t^{-1}, the registration is subject to debate in some countries and its long term future use is not assured.

Inert dusts (e.g. diatomaceous earth formulations) can provide direct alternative to chemical protectants where their adverse effects on grain characteristics and handling are acceptable. In particular, they provide good protection against insect infestation in dry grain stored long term for animal feed. They form a useful part of IPM strategies for grain protection in sprays applied to the storage fabric to minimise residual infestation and migration of pests into the bulks of stored grain. For further detail see Section 4.2.3.2.5.

4.2.4.3.4. Physical control methods

4.2.4.3.4.1. Gamma ray or accelerated electron irradiation

Irradiation of grain, cereals and milled products is effective; little or no further research is required (Brower and Tilton, 1985). It has been demonstrated to be effective at all temperatures with either bulk or packaged commodities. Like methyl bromide treatment, irradiation does not confer residual protection against pests, so irradiated products are susceptible to reinfestation. Although irradiation is accepted by many regulatory authorities, there are perceived consumer acceptance problems. Irradiation facilities require a capital investment that is considered to be high; the need for large, central facilities may require logistical changes. Irradiation may not immediately kill all life stages of pests, although after irradiation at specified dosages all living pests should be sterile. Since irradiation will stop germination of grains and seeds, it is not suitable for commodities requiring germination such as malting barley or mung beans for sprouting. Thus far, irradiation has not been accepted as a quarantine treatment for grains.

A full-scale commercial irradiator for bulk grain has been built at the port of Odessa, Ukraine (Zakladnoi *et al.*, 1982). This had two accelerated electron units each with a capacity to treat 200 t h^{-1}, directly replacing the potential need for methyl bromide fumigation as a rapid disinfestation system. It is reported no longer to be in operation.

A case-study for rice irradiation in Indonesia is attached (Case history 4.2.1).

4.2.4.3.4.2. Heat treatment

Heat treatment is a process which can give complete mortality of insects in grain. It is the very few processes, considered here, with the potential to meet the treatment speeds afforded by methyl bromide fumigation. The process still requires development for large scale use. There are currently no installations which meet the typical handling speeds of large modern grain terminals, often 500 t h^{-1} or more on one belt, but a prototype fluid bed system has been built and successfully run at 150 t h^{-1} (Sutherland *et al.*, 1987).

Pilot and laboratory studies, reviewed by Sutherland *et. al.* (1987) and Banks and Fields (1994), have typically used heated air at 90°C, or greater, as a heat transfer medium into the grain with the objective of heating the grain briefly to above 65°C. Other heat sources, such as microwaves, infra-red or radio-frequency irradiation can also be used (Boulanger *et al.*, 1969; Banks and Fields, 1994), but these have not yet been shown to be superior in practice to hot air-based systems.

Under good process control there is no damage to the end use qualities of treated cereals at levels of heating required to eliminate insect pests. These include breadmaking quality of wheat, rice quality and malting quality of barley (Fleurat-Lessard, 1985; Sutherland *et al.*, 1987). However, the margin of error is small and only slightly excessive treatment can cause some adverse effects (Fleurat-Lessard and Fuzeau, 1991).

Heat disinfestation is one of the very few potential alternatives for disinfestation of bulk grain from live snails (*Cernuella* and *Cochlicella* spp.) (Cassells *et al.*, 1994). Current recommendations against these quarantine pests involve high dosages of methyl bromide (Bond, 1984).

All common stored grain insect pests can be controlled in grain exposed for one week to temperatures lower than -18°C. This type of treatment is preventatively used for the disinfestation of high value grain, such as organically-grown rice, in some developed countries. This technique is efficient but only practicable for small quantities in batches.

4.2.4.3.4.3. Cold treatments

Cooling of grain with aeration is in widespread use in temperate climates. Aeration is a part of many pest management programs and plays a most important role in preventive control measures at a cost sometimes competitive with curative disinfestation processes such as fumigation with methyl bromide (Armitage *et al.*, 1991).

The use of moderately low temperatures to control infestations by storage pests has long been recommended (Burgess and Burrell, 1964; Navarro *et al.*, 1990). Recent developments have shown that many grain bulks in temperate climates can be cooled even in summer during the night with ambient air aeration (Armitage, 1987; Lasseran and Fleurat-Lessard, 1991; Berhaut and Lasseran, 1986). Cooling grain during winter to reach a temperature level below 5°C can give a high mortality of stored product pests if kept under these conditions for at least four months. However, some adult pests may still survive. Each store must be equipped with appropriate ventilation ducts and ports with fans controlled to give optimum cooling performance for particular ambient conditions.

Where ambient conditions are unfavourable for normal aeration, with high temperature or humidity, air dehumidified and chilled using a refrigeration unit may be used for the aeration. Many grain silos in the Mediterranean and subtropical regions use this process (Brunner, 1986). The temperature of the grain soon after harvest is reduced in a few days below the development temperature threshold of the main insect pests. This process can be part of an overall pest management strategy which does not include the need for fumigation with methyl bromide. A single refrigeration unit is used for several bins in a silo system, each bin being refrigerated in turn for a few days. The equipment is energy consuming and can be expensive.

4.2.4.3.5. Biological control methods

4.2.4.3.5.1. Biological control with predaceous insects or parasites

This is not regarded as a replacement for methyl bromide, but potentially as part of an IPM strategy reducing dependance on methyl bromide.

4.2.4.3.5.2. Insect pathogens of microbial origin

Bacillus thuringiensis (Bt) provides control of almond moth and Indian meal moth when applied to grain as an aqueous suspension or as a dust. It is effective as a bulk treatment where all grain is treated or when several inches below the surface layer is treated, lepidopterous larvae are usually living on the bulk-grain surface or near the surface. Potentially, Bt and other pathogens can form part of an IPM strategy.

4.2.4.3.5.3. Pheromones

Use of pheromones has not been developed as an effective means of general control for insect pests of cereals. They appear more suited as tools within an IPM strategy for the early detection of insect infestations. Nevertheless, when insect populations are low, mass-trapping with pheromones (Trematerra, 1991) can effectively limit multiplication of moth pests of grain, and possibly maintain the population under the economic threshold (Fleurat-Lessard, 1986; Trematerra, 1988; Burkholder, 1985).

4.2.5. Substitutes in dried fruit and nuts

4.2.5.1 Definition of commodities and pests

Two groups of commodities are described in this section - nuts and dried fruits - both of which possess diverse physical and chemical characteristics. These commodities may be stored for extended periods of time, both before and after processing. They may be both domestic and foreign in origin, and quarantine treatments may be necessary in some cases. The alternatives to methyl bromide are likely to be more insect and commodity specific than current practices. They are also likely to be more expensive and require higher technological input. Overall, substitution of methyl bromide, currently the dominant means of disinfestation of dried fruit and nuts worldwide, is likely to need an IPM approach using a variety of methods of pest control together to achieve the same goal: pest free and undamaged product at point of export or sale.

Commodities in this category, at least sometimes treated with methyl bromide and associated target pests, are given in Tables 4.2.4 and 4.2.5.

Table 4.2.4 Varieties of nuts and fruits sometimes treated with methyl bromide

Common name	Scientific name
Nut Varieties	
Almond	*Prunus amygdalus*
Beechnut	*Fagus* spp.
Betel nut	*Areca catechu*
Brazil nut	*Bertholletia excelsa*
Butternut	*Juglans cinera*
Cashew	*Anacardium occidentale*
Chestnut	*Castanea* spp.
Coconut	*Cocos nucifera*
Cola-nut	*Cola acuminata*
Hazelnut (filbert)	*Corylus* spp.
Hickory nut	*Carya* spp.
Macadamia nut	*Macadamia tenuifolia*
Pecan	*Carya illinoensis*
Pinenuts	*Pinus* spp.
Pistachio	*Pistacia vera*
Walnuts	*Juglans* spp.

Dried Fruits

Apple	*Malus* spp.
Apricot	*Prunus armeniaca*
Banana	*Musa* spp.
Blueberry	*Vaccinium* spp.
Cherries	*Prunus cerasus*
Cranberry	*Vaccinium macrocarpon*
Date	*Phoenix dactylifera*
Fig	*Ficus carica*
Mango	*Mangifera indica*
Papaya	*Carica papaya*
Peach, nectarine	*Prunus persica*
Pear	*Pyrus* spp.
Pineapple	*Ananas comosus*
Prune	*Prunus domestica*
Raspberry	*Rubus idaeus*
Sultanas, currants and raisins	*Vitis* spp.
Tomato	*Lycopersicon esculentum*

Table 4.2.5 Target pests of dried fruits and nuts

Scientific name		Common name	Host[a]
Acarus siro		Flour mite	F
Alphitobius laevigatus		Black fungus beetle	N
Amyelois transitella	*	Navel orange worm	F, N
Anarsia lineatella		Peach twig borer	F, N
Araecerus fasciculatus		Coffee bean weevil	F
Cadra figulilella		Raisin moth	F, N
Carpoglyphus lactis		Dried fruit mite	F
Carpophilus spp.		Dried fruit beetles	F, N
Cryptolestes ferrugineus		Rust red flour beetle	N
Cryptolestes pusillus		Flat grain beetle	N
Curculio carvae		Pecan weevil	N
Curculio nasicus	*	Curculio	N
Cydia caryana		Hickory shuckworm	N
Cydia pomonella	*	Codling moth	F, N
Dermaptera		Earwigs	F
Dermestidae		Dermestids	N
Drosophila spp.		Vinegar flies	F
Ephestia cautella	*	Almond moth	F, N
Ephestia elutella		Warehouse moth, tobacco moth	F, N
Forficula auricularia		Common earwig	F
Formicidae		Ants	F, N
Lasioderma serricorne		Cigarette beetle	F, N
Oryzaephilus mercator		Merchant grain beetle	F, N
Oryzaephilus surinamensis	*	Saw-toothed grain beetle	F, N
Plodia interpunctella	*	Indian meal moth	F, N
Spectrobate ceratoniae		Carob moth	F
Stegobium paniceum		Drugstore beetle	N
Tephritidae	*	Fruit flies	F, N
Tribolium castaneum	*	Red flour beetle	N
Tribolium confusum		Confused flour beetle	F, N
Trogoderma granarium	*	Khapra beetle	F, N
Typhaea stercorea		Hairy fungus beetle	F
Vitula edmandsae serratilinella		Dried fruit moth	F

[a] F = principally dried fruit pest, N = principally pest of nuts

*Major pests

4.2.5.2 Scope of the problem

Pests of dried fruits and nuts can be found any time after harvest and until eventual consumption. These pest problems occur internationally, but there may be some pest species of importance only regionally.

Some of the pests originate in the field and do not persist and reproduce in storage (e.g. codling moth, Dandekar, 1989), while others are the stored product pests (e.g. saw-toothed grain beetle) which may attack a wide range of commodities apart from dried fruit and nuts (e.g. grain). The field pests may require treatment to meet quarantine or phytosanitary requirements of producer or importing countries, while the stored product (storage) pests must be treated in order to avoid damage to the product as well as sometimes to meet market or regulatory standards. Reinfestation by storage pests may occur in local and importing country storage, during transit and subsequently in marketing channels and consumer storage.

Most dried fruits and nuts are harvested over a relatively short period and at the same time August to November in the northern hemisphere. Therefore, very large volumes have to be treated quickly. For instance, receiving stations in the USA can handle 26,000 tons per day of dried fruits and nuts at the peak of the season. The average yearly world production of only 6 of the 35 listed commodities is approximately 3.3 million metric tons (see Table 4.2.6 below). Based upon a conservative value of $US1.43 per kg, the farm value of these 6 commodities is of the order of $4.8 billion per year. The remaining 29 commodities place the value of the world production of dried fruits and nuts in excess of $10 billion. Obviously, these high value commodities require high quality insect control, particularly when value-added costs are considered. Currently, most dried fruits and nuts are treated at least once with methyl bromide. The frequency depends on the time interval in storage prior to processing (over one year, in some cases) and local conditions. Loss of methyl bromide is predicted to have (Anon., 1993a) a severe impact on the costs of pest control, as currently used, and secondary or indirect effects on storage, handling, and processing for both domestic and foreign markets need to be considered.

Table 4.2.6 World Production of Main Dried Fruits and Nut Crops.
3 Year Average (1990/91 - 1992/93)

Commodity	Quantity (t)
Prunes	315,498
Raisins, sultanas and currants	910,098
Almonds	526,823
Walnuts	573,928
Hazelnuts	863,647
Pistachios	153,077
Total	**3,343,071**

Source: Horticultural Products Review, USDA/FAS, 1993

A recent USDA-sponsored workshop (Anon., 1993c) specifically considered the availability and technical feasibility of alternatives to methyl bromide. Participants included research and regulatory personnel as well as key industry representatives. The workshop provided the basis for some of the recommendations in this section.

Of particular concern were the extended times for application and treatment, and reduced efficacy of a number of the alternatives. Furthermore, no single alternative has been demonstrated to provide the complete eradication of insects required for quarantine treatments. The development of substitute quarantine treatments to replace methyl bromide will require long term effort, not only for developing efficacy data, but also for gaining regulatory acceptance. Some commodities may be damaged by the alternatives proposed; thus, the alternatives may be commodity specific. A systems approach incorporating several alternatives will be required to provide adequate protection and quarantine security. Considerable engineering and technology transfer will be required for the alternatives to be economical and in place on a timely basis. Enclosures can vary from a few cubic meters to more than 30,000 m^3 treating from a few kilograms to more than 10 million kilograms of commodity. The situation would pose particular difficulties for Article 5 countries.

4.2.5.3 Existing substitutes

Methyl bromide fumigation is currently the only currently approved treatment for quarantine for dried fruit and nuts. Irradiation and controlled atmospheres are currently not used to any great extent for dried fruits/nuts (see advantages/disadvantages of each below).

There are a variety of techniques which can potentially be used to control storage pests of dried fruit and nut pests. An IPM strategy, involving a number of techniques, may be required if the need for methyl bromide treatments is to be reduced substantially.

Dried fruit and nuts have particular quality characteristics which must be taken into account when considering application of technologies developed for pest control. In particular, sultanas, raisins and currants are susceptible to sugaring when held at low temperatures, and sultanas may change colour (increased brownness) and lose grade when subject to high temperatures for extended periods. Other technologies may be beneficial, e.g. nitrogen-based CA, in controlling rancidity as well as pests in some nuts.

Alternatives to methyl bromide treatments, specifically for dried fruit and nuts, are set out below.

4.2.5.3.1. Phosphine

This fumigant is used to control stored product pests (Nelson, 1970; Hartsell *et al.*, 1991). It is already in use for control of pests of dried vine fruit in storage and no further research is needed. Most pests of dried fruit and nuts are highly susceptible to phosphine and shorter exposure times can be used than with stored grain. In the latter case, longer periods are needed to control *Sitophilus* spp. These do not attack dried fruit or nuts. Advantages include: registered; efficacious for relevant pests; relatively cost effective; widely accepted; and low residues. Disadvantages include: fumigation time of 3 to 12 days; off-flavour in some commodities, e.g. walnuts; not effective under 10°C in dried fruit and nuts; corrosive to copper and alloys; vacuum fumigation is not recommended because of possible explosion hazard. In most countries phosphine can be used on dried fruits and nuts, with the exception of walnuts. Phosphine has not been developed to a level approved for quarantine treatments.

4.2.5.4 Other fumigants and gases

4.2.5.4.1. Hydrogen cyanide

Not currently in use on dried fruit and nuts and no longer registered in most countries. Dried vine fruit tend to absorb hydrogen cyanide with formation of quite stable cyanhydrins.

Advantages: efficacious against stored product pests. Disadvantages: bad public image; explosive and flammable.

4.2.5.4.2. Ethyl formate

In use in some countries (e.g. Australia, South Africa) as a fumigant for packaged dried vine fruit, directly substituting for the need for methyl bromide treatment soon after packing.

Advantages: efficacious against stored products pests; and can penetrate packaging material. Disadvantages: flammable and explosive; not registered for use in USA and Europe; 72-hour minimum exposure required for efficacy; corrosive to unpainted metals, especially iron and steel.

4.2.5.5 Controlled atmospheres

Modification of air space to suffocate insects (low O_2, high CO_2 or high N_2 or hyperbaric pressure) requires purging and displacing atmosphere (Soderstrom *et al.*, 1984; Navarro and Donahaye, 1990). Some research on sealing and efficacy may be required.

Controlled atmospheres (CA) have been used to some extent to replace methyl bromide for disinfesting dried fruits and nuts. The latest method under development (Reichmuth, 1990), combines carbon dioxide with high pressure of 20 to 40 bar and controls all stages and species of pest insects within less than three hours. It requires a gastight chamber which can withstand pressure of this magnitude and will be capital intensive to install.

Treatment of almonds in silo with CA has been successfully demonstrated under full scale commercial conditions (Soderstrom *et. al.*, 1984). Use of CO_2 as an alternative to methyl bromide has been successfully trialled for sultanas in cartons in stacks (Tarr *et al.*, 1994), and in export freight containers (Banks *et al.*, 1993). Improvements in on-site generation of nitrogen (Navarro and Donahaye, 1990; Banks *et al.*, 1993) and improved quality retention under CA may make CA treatments an attractive alternative to methyl bromide. Some modification of sealing techniques, already developed for stored grain (e.g. Ripp *et al.*, 1984; Annis and Graver 1990), will be required to suit the dried fruit and nut industries.

Advantages include: absence of residues; proven efficacy; and decreasing cost of nitrogen production technology. Disadvantages include: need for well-sealed enclosures; often high capital and operating costs; slow acting, long time period necessary (1 - 2 weeks); temperature dependent and only slowly effective under 15°C; no residual activity; not accepted for quarantine; will require retraining on the process and its variables; unless maintenance levels are used, commodity is immediately susceptible to reinfestation (as is the case with all fumigants).

4.2.5.6 Contact insecticides and inert dusts

Malathion. Advantages include: short-term residue; and history of usage in the grain industry. Disadvantages include: odour, surface protectant only, no penetration and potential residue and resistance problems.

Inert dusts. Even though they may be efficacious in controlling insect pests, they are not likely to be used because of quality and consumer acceptance problems.

Insect growth regulators. These include insect hormones or synthetic analogues capable of affecting insect growth, development, and reproduction (Mkhize 1986; Samson *et al.*, 1990). These can be used only as protectants. Advantages include: demonstrated effective as a protectant of peanuts, rice, and wheat; host specificity; low mammalian toxicity; and long term protection. Disadvantages include: not approved for food products; not approved for quarantine; slow acting; and host specificity.

4.2.5.7 Physical methods

4.2.5.7.1. Irradiation

Irradiation of dried fruits and nuts is effective (Kader *et al.*, 1984; Rhodes, 1986); this effectiveness has been commercially demonstrated. Irradiation does cause off flavour in walnuts above 0.9 kGy. Irradiation, as methyl bromide fumigation, does not confer residual protection on commodities and irradiated products are immediately susceptible to reinfestation. Irradiation is not temperature dependant and bulk or packaged product can be treated. Although irradiation is generally accepted by international trade and regulatory agencies, there are perceived consumer acceptance concerns. High capital costs, logistics and the possible presence of live but sterile pests have been mentioned as possible problems in application of this technology. Thus far, irradiation has not been accepted as a quarantine treatment for these commodities.

4.2.5.7.2. Optimised hot and cold treatments

Both heat and cold treatments have potential as disinfestation procedures for specific dried fruit and nuts. Both will need to be researched carefully before adoption to determine effects on quality of the treated product. It is already known that low temperature storage of processed sultanas can lead to sugaring and high temperature storage or treatment of many dried fruit and nuts can lead to detrimental colour change or rancidity. Heat treatments may be capable of development for dried fruit and nuts as a rapid alternative to methyl bromide treatment.

Cooling to very low temperatures (-10 to -18°C) is an established system of disinfestation of dates, replacing methyl bromide treatment. It is most effective when combined with a brief exposure to low pressure or 2.8% oxygen, which causes insects to leave the centre of the fruit (Donahaye *et al.*, 1992), making them vulnerable to the cold treatment. 10.5 hour exposure to -10°C, or 2.25 hour exposure to -18°C, killed all stages of the relevant insect pests (Donahaye *et al.*, 1991). A similar treatment is increasingly replacing methyl bromide for disinfesting dates in Israel. The utility of very low temperatures as disinfestants needs to be checked for other dried fruit and nuts.

Cooling, combined with nitrogen CA treatment in sealed, white-painted silo bins is in use in Australia for protection and disinfestation of in-shell almonds (Banks, H.J. pers. comm.). Similar technologies may prove suitable for most bulk stored nuts, under appropriate climatic conditions giving high quality storage without need for periodic methyl bromide treatments.

Advantages include: no residues; public acceptance; environmentally safe; and worker safe. Disadvantages include: not currently accepted for quarantine treatment; exposure time may affect quality; needs uniformity of application; no residual activity, high energy costs; at low temperatures can cause sugaring of dried fruit.

4.2.5.8 Biological methods

Further data is needed before biological methods can be confidently applied in dried fruit and nuts. In particular, information is needed on insect commodity preferences and effect of commodity and environmental conditions on insect growth and development, survival, and reproductive capacity (Johnson *et al.*, 1992; Vail *et al.*, 1993a, 1993b). This data should assist in the evaluation of proposed treatments using microbial pathogens, mating disruption and classical biological control in the dried fruit and nut industry. It would also assist in determining the best role of biological methods in an IPM system.

Microbial control involves use of insect-specific pathogens for control. It can be used primarily for long-term protection after an initial disinfestation treatment (Hunter, 1973; McGaughey, 1986; Cowan *et al.*, 1986; Vail *et al.*, 1991). Advantages include: no chemical residues; specificity; long term protection; potential to reduce number of chemical treatments required.

Disadvantages include: may be too specific; registration and labelling issues; not readily available; yet to be accepted by consumer, commodity, and regulatory agencies.

Mating disruption - This control method is based on behaviour modifying chemicals, i.e. pheromones, to control insect mating and reproduction. Advantages include: host specificity; compatibility with other methods; worker safe and environmentally safe. Disadvantages include: used only as protectants, not as an eradication method; not likely to be acceptable for quarantine use; species specific and probably will control only low populations.

Classical biological control - This involves use of predators and parasitoids for insect control (Press *et al.*, 1975, 1982; Brower 1988a, 1988b; Cline and Press 1990). This method can be used primarily as a space treatment when commodity is not present. There appears to be a role for biological control of moth pests, often the main pest of dried fruit and nuts as part of an IPM program. They are quite susceptible, and several effective predators and parasitoids are available. Advantages include: long-term population suppression; specificity; worker safe; and environmentally safe. Disadvantages include: host specificity; availability; not for quarantine: quality control; and not compatible with chemicals.

4.2.5.9 Others

4.2.5.9.1. Packaging and containerisation

This involves use of insect-resistant packaging for bulk and consumer packed goods. This method may be used as a treatment by itself or after other treatment to prevent re-infestation. Advantages include: unitised packaging could limit infestations and losses; can be used in combination with controlled atmospheres, irradiation and other technologies; provide protection in marketing channels and may eliminate need for large storage facilities. Disadvantages include: problem as to scale; costs; needs to be combined with other technologies; and need for assurance of low infestations when containerised.

4.2.5.9.2. Detection, sorting, certification

These include methods to reduce or determine infestation levels to reduce or eliminate need for specific treatments. Advantages include: environmentally benign; reduce need for treatments; and improved worker safety. Disadvantages include: requires high technology; unknown costs; and regulatory acceptance.

4.2.5.9.3. Engineering

Many of the alternatives will require considerable engineering research in order to be applied efficiently. New methods of application, increased energy efficiency, and sealing methods for existing or new structures will have to be identified or developed. Specific facilities may need to be designed for use of multiple technologies. Advantages include: helpful in maximising the efficiency of newly developed control procedures. Disadvantages: none identified.

4.2.5.9.4 Genetic engineering

Insertion of specific genetic material into plant genomes (transgenic plant straints) to provide insect control (Dandekar 1989; Vail *et al.*, 1991). Advantages include: specificity; no residues; long-term protection; safe; and no energy requirements. Disadvantages include: consumer acceptance; regulatory acceptance; cost of development; and specificity.

4.2.5.9.5 Combination of processes - IPM systems

Many of the processes and technologies given above may be better used in combination, rather than as a 'stand-alone' measure for pest control. In that form they may provide both an alternative to methyl bromide use and improved storage. Examples include use of permanent sheeting over carton stacks of dried vine fruit combined with hygiene and a disinfestation treatment, e.g. CO_2 or phosphine, or use of cooling and CA in a sealed system for nuts. Also, efficient sorting machines, removing damaged or infested nuts could be used in combination with sanitation and packaging, and beneficial insects (predators), to give an acceptable level of control. High efficiency sorting machines may be used together with protectants and/or physical treatment to provide acceptable control levels. Beneficial insects might be used for space treatments and sanitation. Further research is required to substantiate and develop IPM options as alternatives. Advantages include: reduction of need for specific control systems. Disadvantages include: dependence upon control strategies used; more emphasis on sanitation and source reduction is assumed in IPM systems; cost and additional training; difficult for regulatory agencies to monitor; difficult to obtain quarantine approval.

4.2.6. Beverage crops

4.2.6.1 Definition of commodities and pests

Beverage crops include coffee and cocoa beans and tea. Of these, only cocoa beans are commonly infested in storage, though the coffee bean weevil may cause problems in coffee, particularly if stored in poor conditions at high humidity. Tea is only infested by insects arising as cross-contamination from other commodities.

Table 4.2.7 Target pests in beverage crops

Scientific name		Common name
Araecerus fasciculatus	*	Coffee bean weevil
Ahasverus advena		Foreign grain beetle
Carpophilus dimidiatus		Dried fruit beetle
Corcyra cephalonica		Rice moth
Cryptolestes ferrugineus		Rust-red grain beetle
Ephestia cautella	*	Tropical warehouse moth
Ephestia elutella	*	Warehouse (cocoa) moth
Hypothenemus hampei		Coffee berry borer
Lasioderma serricorne		Cigarette beetle
Ptinus tectus		Australian spider beetle
Oryzaephilus mercator		Merchant grain beetle
Tribolium castaneum		Rust red flour beetle

* Major pests

4.2.6.2 Scope of the problem

These high value products are typically produced in developing countries and shipped to developed countries that demand a high standard of quality and total absence of infestation by pests. In many production areas storages are of inadequate quality to protect the commodities from invasion by pests and the ambient high temperatures and humidities may favour their rapid multiplication. Infestations can lead to severe economic losses unless effective control measures are applied. Losses result not only from direct damage and downgrading as a result of pest activity, but also from charges levied by importing countries where compulsory fumigations may be carried out at point of import, should infestations be detected.

Cocoa and coffee beans may be shipped either in bag or bulk, while tea tends to be shipped in ply boxes. Techniques for treatment with methyl bromide, the preferred fumigant by some exporters and also, frequently, by importers, is applied similarly to when it is used on grain.

Some beverage crops, notably cocoa, have high fat content and tend to build up residues of inorganic bromide. This can preclude multiple treatments with methyl bromide if residue tolerances are not to be exceeded.

4.2.6.3 Existing substitutes

4.2.6.3.1. Phosphine

Phosphine is widely used to control insects in beverage commodities (Clifford and Wilson, 1985; Wood and Lass, 1990). It is claimed that in certain circumstances phosphine may taint cocoa beans. However, there is no firm evidence of such occurrences when the fumigation is carried out in a well controlled manner according to established procedures. For information on advantages and disadvantages, see Section 4.2.3.1.1 on general attributes of alternatives.

4.2.6.4 Other fumigants and gases

4.2.6.4.1. Hydrogen cyanide

This can be potentially used on beverage crops as an alternative to methyl bromide, but is not currently used for this purpose.

4.2.6.4.2. Controlled and modified atmospheres

For many years, controlled atmospheres have been used to replace methyl bromide for disinfecting beverage crops. A recent innovation combines carbon dioxide with high pressure of 20 to 40 bar and controls all stages and species of pest insects in less than three hours. It requires a gas tight chamber which can withstand pressure of this magnitude. It is currently in limited use in Germany (Prozell and Reichmuth, 1990).

4.2.6.5 Contact insecticides

Contact insecticides are not applied directly to these products. However, they may be used as part of an IPM program to protect bagged products from insect invasion, using surface application to the bags and the store fabric.

4.2.6.6 Physical methods

4.2.6.6.1. Irradiation

In cocoa, a dose of 0.8 kGy caused a 100% mortality of *Ephestia cautella, Lasioderma serricorne, Araecerus fasciculatus*, and *Tribolium castaneum* within five days of irradiation (Appiah, undated; Amoako-Atta, undated). At that dose, the cocoa beans still met the highest quality standards, a measurement that includes insect damage. A dose of 0.50 kGy prevented adult emergence from the irradiated eggs and younger larvae, while doses of 0.10 - 0.25 kGy eliminated adult survival from the irradiated older larvae and pupae (Manoto *et al.*, 1987; Appiah *et al.*, 1981). The process is not in commercial use for cocoa beans.

Herbal teas have been commercially irradiated to eliminate bacterial contamination at a higher dose than required for disinfestation. While irradiation has not been used commercially to disinfest cocoa or coffee, the process has been shown in research studies to be effective. Indonesian researchers recommended a dose higher than 0.40 kGy be used to obtain 100% mortality of pests infesting coffee within one week (Hoedaya *et al.*, 1985, 1987). Research in Brazil and the Philippines showed that a dose of 0.50 kGy was sufficient to result in about

98% mortality of adult coffee bean weevil and prevent adult emergence from irradiated eggs (Manoto *et al.*, 1987).

4.2.6.6.2. Temperature Control

Heat and cold can potentially be used to control insects in beverage crops in bag or in bulk. Methods need to be developed and trialled.

4.2.7 Herbs and spices

4.2.7.1 Definition of commodities and pests

The fruits, leaves and other parts of many dried plants are used for medical and food purposes. Many of these materials are subject to infestation by stored product pests and may be treated with methyl bromide as one of the measures used for their control.

Table 4.2.8 Herbs and spices sometimes disinfested with methyl bromide

Common name	Scientific name
Basil	*Ocimum basilium*
Bay	*Laurus nobilis*
Chillies	*Capsicum* spp.
Cinnamon	*Cinnamonum zeylanicum*
Cloves	*Syzygium aromaticum*
Coriander	*Coriandrum sativum*
Fenugreek	*Trigonella feonum-graecum*
Ginger	*Zingiber officianale*
Marjoram	*Origanum marjorana*
Mint	*Mentha* spp.
Mustardseed	*Brassica juncae*
Nutmeg/mace	*Myristica fragrans*
Oregano	*Origanum vulgare*
Parsley	*Petroselinum crispum*
Pimento	*Pimenta dioica*
Rosemary	*Rosemarinus officianalis*
Saffron	*Crocus sativus*
Sage	*Salvia officianalis*
Sesame	*Sesamum indicum*
Tarragon	*Artemesia dracunculus*
Thyme	*Thymus vulgaris*
Turmeric	*Curcuma domestica*
Vanilla	*Vanilla fragrans*

Table 4.2.9 Some target pests in herbs and spices

Scientific name		Common name
Araecerus fasciculatus		Coffee bean weevil
Ephestia cautella		Rice moth
Lasioderma serricorne	*	Cigarette beetle
Necrobia rufipes		Copra beetle
Oryzaephilus spp.	*	Grain beetles
Plodia interpunctella		Indian meal moth
Stegobium paniceum	*	Drugstore beetle
Tribolium spp.	*	Flour beetles

*Major pests

4.2.7.2 Scope of the problem

These high value products are usually grown in tropical regions. They may become infested prior to harvest, or in store in the country of production. These infestations can lead to severe economic losses if no control procedures are applied.

Methyl bromide is currently used for insect pest control in a variety of spices and herbs. Treatments are mostly bagged and baled commodities, either under gas proof sheets in warehouses, in chambers or in shipping containers. Products may also be fumigated during sea transit in shipping containers. Dosages of methyl bromide vary between 15 to 30 g m^{-3}, and exposure periods are in the range of 1 to 2 days. Residue of inorganic bromide can accumulate, particularly in products with high fat and protein content. Multiple fumigations should therefore be avoided to ensure permitted residue levels are not exceeded.

Many spices and herbs are produced under conditions where there may be excessive bacterial contamination for particular markets. Treatments with fumigants other than methyl bromide are normally used to sterilise herbs and spices. These will normally control pests too.

4.2.7.3 Existing substitutes

4.2.7.3.1. Phosphine

Phosphine is often used to disinfest herbs and spices, particularly where there may be the possibility of excessive residues with methyl bromide.

4.2.7.4 Other fumigants and gases

4.2.7.4.1. Ethylene oxide

Some countries still allow the use of ethylene oxide for pest control. It is the fumigant of choice where sterilisation, as well as pest control, is required. This substance has been withdrawn widely due to its reaction with chloride and bromide in commodities to produce potentially carcinogenic compounds. Ethylene oxide should not be used on herbs, vegetable seasonings or spice mixtures that include salt because of formation of these materials. Apart from MeBr, phosphine and ethylene oxide, there are no other fumigant gases used for pest control in these products.

4.2.7.4.2. Controlled and modified atmospheres

Carbon dioxide or nitrogen-based controlled atmospheres are very useful alternatives for methyl bromide for pest control in herbs and spices. Since many of the processing factories already have gas-tight chambers, a change from methyl bromide to controlled atmospheres might not be too difficult. The main change would be the increase in the treatment period to 2 to 6 weeks depending on the temperature and species of the insect to be controlled. The latest method (Prozell and Reichmuth, 1990; Reichmuth, 1990) combines carbon dioxide with high pressure of 20 to 40 bar and controls all stages and species of insects within less than three hours. It requires a gas-tight chamber which can withstand pressure of this kind and may require high capital investment.

4.2.7.5 Contact insecticides

High value products such as herbs and spices are often directly used for human consumption without any further processing. These are, therefore, not normally treated with any substances with contact insecticides because of potential problems.

4.2.7.6 Physical control methods

4.2.7.6.1. Irradiation

Spices, herbs and vegetable seasonings are commercially irradiated for control of bacterial contamination in many countries. The dosages necessary for this purpose are higher than those required for disinfestation from insect pests. (Marcotte, 1994; Jategaonkar and Marcotte, 1993; Katusin-Razem *et al.*, 1985; Saint-Lebe *et al.*, 1985; Urbain, 1986). For most of these products there are no significant changes in sensory evaluations as a result of irradiation in the dose range of 5.0 - 10.0 kGy, sufficient for sterilisation, and thus no adverse effects can be expected at the much lower dosage required for insect pest control.

4.2.7.6.2. Heat and cold treatments

Since herbs and spices contain volatile compounds which are responsible for their identity and quality, heat treatments are usually avoided. Cooling to a sub-zero temperature may preserve the quality and can also serve as a control measure against insect pests. Both approaches appear to be promising as alternatives to methyl bromide for specific products, but require further research to show they can effect disinfestations while not adversely affecting quality.

4.2.8 Tobacco

4.2.8.1 Definition of commodities and pests

Tobacco is a high value commodity which is transported internationally either raw or as finished products (cigars, cigarettes). In the trade, a nil infestation is generally expected.

Table 4.2.10 Target pests in tobacco and related products:

Scientific name		Common name
Ephestia elutella	*	Warehouse moth, tobacco moth
Glycyphagus domesticus		House mite
Phthorimaea operculella		Potato tuber moth
Lasioderma serricorne	*	Cigarette beetle

* Major pests

4.2.8.2 Scope of the problem

Methyl bromide was formerly used to control tobacco pests in many countries (Manzelli, 1987). Nearly 40% of the 81 organisations from 43 different countries declared that they use methyl bromide. Even though the treatments are very efficient, they are usually more expensive than with phosphine. There are indications now that fewer countries are using methyl bromide for tobacco fumigation in storage, and its use generally is declining for this purpose.

In France, for example, methyl bromide is now little used to control insects during tobacco storage. Only the harbour unit of Le Havre, under the control of the Plant Protection Department of the Ministry of Agriculture, fumigate imported tobacco with methyl bromide. In most countries, methyl bromide is used under vacuum, but, in some cases, it is applied at atmospheric pressure under gasproof sheets.

The main advantages of methyl bromide are that it can be used at atmospheric pressure or under vacuum at low temperatures and it kills all development stages of the insects. One disadvantage (Benezet, 1989) is its adverse effects on the flavour of the tobacco product. Methyl bromide dosage rates vary from 20 to 100 g m^{-3} depending on conditions, with a 4 h exposure under vacuum or 72 h at normal atmospheric pressure.

4.2.8.3 Existing substitutes

4.2.8.3.1. Phosphine

In those areas where the ambient temperature is above 15°C, phosphine is predominantly used globally for tobacco disinfestation. It is used at atmospheric pressure, has excellent penetration and is effective against all development stages of insects. The rate of use varies between 1 and 4 g m^{-3} and the duration of treatment from 5 - 15 days according to the temperature (Geneve, 1972; Geneve *et al.*, 1986).

4.2.8.4 Contact insecticides

Methoprene, an insect growth regulator, is finding increasing use in stored tobacco against the principal pest, *Lasioderma serricorne*, removing the need for methyl bromide (or other) treatments.

4.2.8.5 Physical control methods

4.2.8.5.1. Irradiation

Irradiation studies on cigarette beetle, *Lasioderma serricorne*, indicated that a dose in the range of 0.6 - 1.0 kGy can control all developmental stages. A dose of 5.0 kGy had no effect on nicotine content, volatile oil content, composition or pH of tobacco (Hoedaya *et al.*, 1987).

4.2.8.5.2. Heat and cold treatment

The lethal effects of a range of exposures of extreme temperature to adults, pupae, four-week-old larvae, two-week-old larvae and eggs of the cigarette beetle, *Lasioderma serricorne* , have been investigated (Meyer, 1980). Adults were generally the most susceptible and large larvae the most resistant stages to both hot and cold temperatures in the laboratory. Pupae were also very susceptible to cold temperatures. All stages could withstand up to 3 hours at -15°C. At 50°C the lethal exposure for larvae was 3 hours and at 55°C an exposure of 1 hour was lethal. At the higher temperatures, ranging from 60°C to 70°C, an exposure of 6 to 15 minutes was lethal at all stages (Meyer, 1980).

4.2.9 Artefacts

4.2.9.1 Definition of commodities and pests

Many of the objects held in museums, libraries and similar repositories are subject to attack by insect pests and, at high humidity, by fungi. Infestable materials include those made of wood, paper, leather and skins, feathers, natural fibres (particularly wool). Artefacts and similar objects made of organic materials (e.g. natural history specimens) are also objects of trade internationally and may carry pests of quarantine significance.

Some of the pests attacking artefacts are listed in Table 4.2.11.

Table 4.2.11 Some common pests of artefacts made of wood, skin, feathers, wool and other organic materials

Scientific name		Common name
Anobium punctatum	*	Furniture beetle
Anthrenus spp.	*	Carpet beetles
Attagenus pellio		Museum beetle
Dermestes lardarius		Larder beetle
Dermestes maculatus		Hide beetle
Dinoderus minutus		Smaller bamboo shot hole borer
Hylotrupes bajulus		House longhorn beetle
Lasioderma serricorne		Cigarette beetle
Lyctus spp.		Powder-post beetles
Stegobium paniceum	*	Drugstore beetle
Tinea spp.		Clothes moths
Tineola bisselliella	*	Clothes moth
Trogoderma granarium		Khapra beetle

* Major pests

Pest insects are often hidden deep in the material and can effectively and quickly be treated with fumigants with high penetrability. In some cases heat and cold are used as lethal treatments. Methyl bromide has been the fumigant of choice in many cases of pest control in artefacts.

If there is a risk that artefacts may harbour a pest of quarantine significance, notably *Trogoderma granarium*, many quarantine authorities will impose a mandatory methyl bromide treatment.

4.2.9.2 Scope of the problem

Artefacts can be severely damaged by attack from only one insect. Some artefacts are of substantial value or may be of irreplaceable cultural significance. Museums are acutely aware of this fact and try to avoid infestation and damage to their most valuable and unique objects. Therefore, many museums have installed a quarantine system which ensures that only insect-free artefacts are stored. Infested artefacts are fumigated in gas tight chambers, sealed rooms or under gas proof plastic sheets.

Methyl bromide is typically applied at 24 g m^{-3} over 24 h at atmospheric pressure or 50 g m^{-3} for 24 h under vacuum in gastight chambers. About 90% by weight of the applied gas is estimated to be emitted to the atmosphere (Unger *et al.*, 1992).

4.2.9.3 Existing substitutes

Methyl bromide use on artefacts is now declining in some countries and being replaced by a choice of alternatives, each with particular advantages and disadvantages. The choices for pest control on museum artefacts have recently been reviewed (Pinniger, 1991).

4.2.9.3.1. Phosphine

Phosphine is used to fumigate wooden objects, paper and other materials of vegetable origin. With some materials, e.g. furs, phosphine may be preferred over methyl bromide, because of the reduced risk of taint. Because the gas may adversely effect metals and pigments in paintings it is rarely used for treating objects of this type. Fumigation with phosphine will require a longer exposure period than methyl bromide for complete control of insects.

4.2.9.4 Other fumigants and gases

Carbonyl sulphide and ethyl formate may be alternatives to MeBr, but no practical data are available on their use for this application. Sulphuryl fluoride is widely used to control wood-destroying insects, but usually not used for artefacts at present. Hydrogen cyanide is also used for pest control in artefacts, with a recommended dosage of 20 g m^{-3} for 72 hours exposure. Hydrogen cyanide is in very limited use because of its high solubility in water, low fungicidal effect and slow desorption, as well as possible reaction with the treated material.

4.2.9.4.1. Controlled/modified atmospheres

Controlled atmospheres are being increasingly used for insect control in artefacts, although depending on the temperature, treatment may take two to eight weeks in a gas-tight chambers (Newton, 1993). There is limited but increasing use of controlled atmospheres for artefacts in Germany (Reichmuth *et al.*, 1992), the UK and possibly elsewhere.

4.2.9.5 Contact insecticides

Contact insecticides, including dichlorvos, may be used as part of pest management strategy in museums and repositories.

4.2.9.6 Physical methods

4.2.9.6.1. Irradiation

Irradiation has been used to control insect and fungal problems in historical artefacts, art objects, books and paper archives with good results in France, Czechoslovakia and China.

Ornamental wood products are sometimes irradiated commercially against pests in Australia after importation from Indonesia (Marcotte, 1994). The minimum recommended dose for pest control ranged between 0.50 kGy for pest control to 1.6 kGy and 18 kGy to control fungal infections (Ramière, 1982; Fan *et al.*, 1988; Anon., undated).

4.2.9.6.2. Heat and cold treatment

Heat and cold treatment can be used with care to disinfest artefacts provided condensation and cracks in wood and other sensitive materials can be avoided by appropriate control of moisture. Exposure to -18°C can give disinfestation of woollen artefacts from clothes moths in a few days (Brokerhof *et al.*, 1994).

4.2.10 Logs, timber, bark and wood products

Treatment of export logs or at point of import, is a major use of methyl bromide fumigation. The treatments are typically against quarantine pests and are required by plant quarantine authorities as a condition of importation.

Methyl bromide has been in use for timber treatment for many years. Its continued successful use has tended to restrict possible development of alternatives.

Two major classes of pest require control: insects and fungi. There may also be instances where control of mites, snails and slugs, and/or nematodes, may be needed. All of these classes of pest include species declared in some countries as specific objects of quarantine.

4.2.10.1. Insect control

4.2.10.1.1 Definition of commodities and pests

Commodities: Logs, timber and bark products such as particle board, wood chips as well as wooden products, containers, pallets toys and sports goods all come under either phytosanitary or quarantine regulations in international trade. Minor uses such as for cotton, packaging materials used for brassware also require quarantine treatments.

Target pests: Target pests and some wood-based commodities are subject to plant quarantine regulations and may be specific in each country. In some countries, particle board, wood chips for pulp and timber for building as well as wooden products such as containers, pallets, instruments, toys, sport goods and even plywood are subject to plant quarantine. When pests are found during inspection, the consignments are treated at the port of importation. Some countries are required to include phytosanitary certificate with export consignments.

Table 4.2.12 Target insect pests in logs, timber and bark products.

Scientific name		Common name
Acanthocinus		Pine bark borers
Arixyleborus spp.		
Cerambycidea scolytidea	*	Longhorn beetle
Dentroctonus spp.	*	Book beetles
Diapus pusillimus		Walnut pinhole borer
Diapus quinquespiratus		
Gnathotrichus retsus		Ambrosia beetle
Gnathorticus sulcatus		Ambrosia beetle
Hylastes ater		Black pine bark beetle
Ips spp.		Bark beetles
Lyctus spp.	*	Powder-post beetles
Monochamus spp.	*	Sawyer beetles
Orthotomicus suturalis		Bark beetles
Platypus spp.		Ambrosia beetles
Polygraphus subopacus		Bark beetle
Rhagium spp.		
Scolytus spp.	*	Bark beetles
Tetropium cinnamopterum		Eastern larch borer
Trypodendron lineatum		Striped ambrosia beetle
Urocerus gigas	*	Woodwasp, Sirex
Xyleborus spp.		Ambrosia beetles
Xylothrips spp.		

*Major pests

4.2.10.1.2 Scope of the problem

Treatments of timber may be carried out as part of a routine export system, or they may be ordered as a result of detection of pests on importation. Principal insect pests are given in Table 4.2.12.

Treatments are normally carried out for logs, timber and bark materials either under gas-proof sheets or on board ships. A dose of 32 g m^{-3} at temperatures of 15°C or over is normally applied when fumigated under gas-proof sheets of 150 micron thickness for a 24 hour period. For in-ship fumigation a dose of 48 g m^{-3} is recommended for the same period of exposure.

Methyl bromide is absorbed significantly by woody materials and only slowly released at the end of a fumigation. It is estimated (Annex 3.1) that about 88% of the methyl bromide applied to logs in ship's holds is released to the atmosphere over a period of 1-2 weeks subsequent to treatment.

4.2.10.1.3 Existing substitutes

It will be noted that while there are a variety of potential substitutes, research is required to establish them as satisfactory treatments that meet standards required by quarantine authorities.

4.2.10.1.3.1. Phosphine

Fumigation of logs using phosphine is effective in controlling bark beetles, wood-wasps, longhorn beetles and platypodids at a dose of 1.2g m^{-3} for 72 hours exposure at the temperature of 15°C or more. This schedule is registered only in the United States. The length of time required to complete treatments restricts its commercial acceptability.

4.2.10.1.3.2. Sulphuryl fluoride

This is effective against major insect pests of timber, including bark beetles, wood-wasps, longhorn beetles, powderpost beetles and dry wood termites. It is applied for log disinfestation and for fumigation of dwellings in the USA. Generally, the dose applied is 64 g m^{-3} for 16 hours exposure at a temperature of not less than 21°C. Advantages of this gas are that it penetrates very well, and is very effective against all wood infesting adult insects. Disadvantages are that it will only control egg stages at very high dosages and is not registered in many countries. The potential of this chemical needs to be investigated regarding its suitability for timber treatment for plant quarantine purposes.

4.2.10.1.3.3 Contact insecticides

There is an approved treatment for logs to be kept immersed in water for more than 30 days in order to control pests by suffocation. The upper surface of the logs above the water level is sprayed with an insecticide mixture. In Japan, approximately 14% of the logs imported in 1992 were treated using this technique. In the USA and Japan, dip-diffusion treatment in a solution of borate is registered.

4.2.10.1.4 Physical control methods

4.2.10.1.4.1. Irradiation

There are very limited published data on the irradiation of timber and timber products. However, American researchers have reported that a dose of 6 - 8 kGy will kill the nematode *Bursaphelenchus xylophilus*, an economic pest of timber (Eicholz *et al.*, 1990).

4.2.10.1.4.2. Other methods

There are three other methods of treatment available: dry heat, under water dipping and bark removal.

Dry heat treatment could be an alternative for very small amount of logs. However, it does not appear practical for large amounts. Heat treatments (steam or hot water dips) used to control fungi (Section 4.2.10.2.3.1) will presumably give complete disinfestation from insects, mites and snails.

Under water dipping treatment of logs for plywood is a necessary process at it improves the quality of the products. However, it needs broad water area and a long exposure time. There is an approved treatment for logs to be kept immersed in water for more than 30 days in order to control pests. The upper surface of the logs above the water level is sprayed with an insecticide mixture. In Japan, approximately 14% of the logs imported in 1992 were treated using this technique, replacing the alternative methyl bromide treatment.

At present, removing bark from logs prior to export is practiced to a very limited extent as a control measure against pests, particularly bark beetles. Debarking, together with conversion to sawn timber in country of origin, appears to have potential to reduce need for methyl bromide where bark-borne pests are the object of the treatment, including quarantine treatments.

4.2.10.2. Control of fungi

Methyl bromide is sometimes applied for control of fungi in timber, often as a quarantine measure. MBTOC did not review this use and alternatives in detail, and will provide further information at a later date.

4.2.10.2.1 Target pests

Some wood inhabiting fungi which need to be controlled, usually for quarantine purposes, are:

- *Antroida carbonica*
- *Ceratocystis fagacearum*
- *Gloeophyllum sepiarium*
- *Lentinus lepideus*
- *Lenzites sepiaria*
- *Lenzites trabea*
- *Postia placenta*
- *Serpula lacrimans*

Timber, which is infested by *Ceratocystis fagacearum*, is usually fumigated with methyl bromide prior to export to Europe under gas-proof sheets or in chambers at the high rate of 240 g m^{-3} (Liese and Ruetze, 1985). This fungus is regarded as a particular quarantine problem in Europe.

4.2.10.2.2. Contact fungicides ('Wood preservatives')

These are effective against surface-living fungi but will not penetrate deep into the wood to kill the spores. Research is necessary to investigate their combined effectiveness with heat and/or fumigation.

4.2.10.2.2.1. Bifluorides

The timber is immersed in a 10% solution of the chemical for 5 to 10 minutes. No monitoring equipment required. Temperatures must be above freezing. The treatment is not registered in the USA, but is acceptable in many European countries. It is a relatively inexpensive treatment.

Bifluorides are commercially used in Europe and are a component of some preservatives used in the USA. Overall assessment of the alternative in relation with MeBr: a very effective treatment but not approved in all countries.

4.2.10.2.3 Physical control methods

4.2.10.2.3.1. Heat treatment

Steam heat or hot water dips are generally most suitable, but kiln drying or dry heat is suitable for sawn timber. Heat treatment by steam has been shown to eradicate all tested fungi when 66°C is held at the centre of wood for 1.25 hours (Chidester, 1991; Miric and Willeitner, 1990; Newbill and Morrell, 1991). More research using logs is needed. Using microwave energy as a heat source is a possibility but more research is needed. (Vijam, 1983).

4.2.11 Seeds for planting

4.2.11.1 Scope of the problem

Several nematode genera are known to be seed-borne. The most important in agriculture are *Anguina, Aphelenchoides* and *Ditylenchus* (Bacci Del Bene and Cancellara, 1973). Many crop species may be infested, including rice, wheat, leguminous plants and onions (Table 4.2.13

lists some of the nematodes transmitted on seeds). These nematodes may be also transmitted by propagules: bulbs, stolons, and cuttings.

Table 4.2.13 Some nematodes transmitted by seeds:

Nematodes	Seed species		Distribution
Aphelenchoides besseyi	rice	*Oryza sativa*	Asia, America, Africa
A. ritzemabosi	aster	*Callistephus sinensis*	Europe
A. blastophthorus	-	-	-
Anguina tritici	wheat, rye	*Triticum, Secale*	Europe, Asia
A. agrostis	bentgrass	*Agrostis, Lolium*	Europe, USA, Australia
A. funesta	rye grass	*Lolium rigidum*	Australia
A. amsinckiae	?	*Amsincka*	America
Subanguina chrysopogoni	grass	*Chrysopogon fubus*	Asia
Ditylenchus angustus	rice	*Oryza sativa*	Asia, Egypt
D. dipsaci	oat	*Avena*	Europe
	onion	*Allium*	Europe
	shallot	-	Europe
	beet	*Beta*	Europe
	fuller's teasel	*Dipsacus fullonum*	Europe, America
	cat's ear	*Hypochaeris radicata*	America
	lucerne	*Medicago*	Europe, New Zealand
	plantain	*Plantago*	America
	dandelion	*Taraxacum officinale*	America
	clover	*Trifolium*	Europe
	field bean, broad bean	*Vicia faba*	Europe, Africa, Middle East
	carrot	*Daucus carota*	"
	runner bean	*Phaseolus*	"
	pea	*Pisum sativum*	"
	buckwheat	*Fagopyrum sagittatum*	"
	spring vetch	*Vicia sativa*	"
D. destructor	groundnut	*Arachis hypogea*	Africa
Heterodera schachtii	beet	*Beta*	Europe
Panagrolaimus spp.	pearl millet	*Pennisetum americanum*	Asia
Rhadinaphelenchus cocophilus	coconut	*Cocos nucifera*	Tropical America

The increase in international exchanges of seed increases the risk of dispersal of seed-borne nematodes. Regulations and certification schemes are required to improve the chances of limiting the dispersal of these important plant pests.

Methyl bromide is a standard technique for destroying dormant nematodes in seed lots. No harmful effects on seed germination were found after treatment (Strong and Lindgren, 1961) and fumigation of seeds is used as a routine as prevention treatment and application of quarantine measure. Test have been carried out with various combinations of concentrations and exposure times (Marre *et al*., 1983).

Developing countries are particularly dependent upon the use of MeBr for quarantine treatments of seed lots because imports are often only permitted if fumigated in the country of origin or at ports of entry.

At present, there is no single approved alternative to or substitute for MeBr. However, there are substitute chemicals and alternative procedures for specific application which could substantially reduce the use of MeBr.

4.2.11.2 Existing substitutes

4.2.11.2.1. Phosphine

Phosphine is not typically effective against seed-infesting nematodes. However, experimental application of phosphine were effective in controlling nematodes in water suspension (Rout, 1966).

4.2.11.3 Chemical soaking and fumigation

Promising results were obtained in the control of *A. besseyi* (Fortuner and Orton Williams, 1975) by soaking rice in aqueous solution of systemic organophosphorous compounds. The compounds are not phytotoxic. Prasad (1992) eliminated *A. besseyi* in rice seeds by soaking them in a solution of mancozeb and monocrotophos followed by fumigation with phosphine at a dose of 9.3 g m^{-3}.

4.2.11.4 Physical control methods

4.2.11.4.1. Cleaning

As some species are associated with plant debris, thorough cleaning reduces the chance of infestation. Measures such as seed cleaning and physical and chemical control help to limit the risks of infestation by seed-borne nematodes and reduce need for methyl bromide curative treatments.

4.2.11.4.2. Hot water treatment

Hot water treatment may be used to control *Anguina agrostis* in bent grass (*Agrostis stolonifera*), but a treatment of 15 minutes at 52.2°C reduces the germination rate.

Hot water treatment following pre-soaking the seeds provides the most effective control of white-tipped nematode *(A. besseyi)*. This may be a mandatory quarantine treatment. The pre-soaking activates their dormant state and subsequent soaking at 51°C for seven minutes controls the nematode. However, some injury to germination may be observed.

4.2.12 Dried fish, meat and seafood

4.2.12.1 Definition of commodities and pests

Commodities damaged by pests include both saltwater and freshwater dried (cured) fish, dried meat and meat products.

Table 4.2.14 Common pests in dried fish, meat and seafood:

Scientific name		Common name
Acarus siro		Flour mite
Attagenus spp.		Carpet beetle
Dermestes spp.	*	Hide beetle
Necrobia ruficollis		Red-necked bacon beetle
Necrobia rufipes	*	Copra beetle
Trogoderma spp.		Khapra beetle, warehouse beetle
Tyrophagus spp.		Cheese and bacon mite

*Major pests

4.2.12.2 Scope of the problem

Dried fish is particularly prone to infestation by several species of dermestid beetles and to a lesser extent by *Necrobia* spp. Damage caused by dermestids can be particularly severe, and it has been reported from inland fisheries in Africa, that if infestation is not controlled, losses approaching 50% of the commodity can result (FAO, 1981). Dried meat may also become infested by similar insect pests, but no information is readily available on economic losses caused to this product.

Methyl bromide has been recommended for the disinfestation of dried fish in several African countries where experimental trials have been carried out, but little information is available to indicate its commercial use (Friendship, 1990).

4.2.12.3 Existing substitutes

4.2.12.3.1. Phosphine

Disinfestation of dried fish using phosphine has been reported by Friendship (1990) and this fumigant would appear to provide effective control of the common insect pests infesting this commodity.

4.2.12.4 Contact insecticides

Pyrethrins synergised with piperonyl butoxide have been recommended as an aqueous dip for protecting dried fish from insect infestation (Proctor, 1972), and more recently pirimiphos methyl has been recommended for the same purpose (Golob *et al.*, 1987). A maximum residue limit of 10 mg/kg was recommended for pirimiphos methyl by the FAO/WHO Committee on Pesticide Residues (FAO, 1986).

4.2.12.5 Physical control methods

4.2.12.5.1. Irradiation

Irradiation has been used to disinfest dried fish in Bangladesh and the Philippines (Matin and Bhuia, 1990; Manoto *et al.*, 1985)

4.2.13 Reducing emissions

The overall quantity of methyl bromide released into the atmosphere may be reduced by several measures in addition to adoption of alternatives. These include:

- revision of dosage rates to avoid overdosing;
- improvement in gastightness of enclosures to reduce leakage and permit lower dosage rates and prolonged exposure periods;
- reducing the frequency of treatments by preventing or reducing reinvasion of pests subsequent to fumigation.

Methyl bromide dosage schedules (Annex 4.2.4) have been produced with commodities grouped on the basis of their general rate of sorption and penetration of the fumigant. The dosage rates apply to well sealed enclosures such as chambers, freight containers and stacks covered with gas-proof sheets in good condition and only to commodities packed in woven sacks, paper bags, boxes or cartons without special seals or impermeable liners. Although the rates of application vary with temperature, broadly, *ct*-product of 300 g h m^{-3} is preferred for temperatures below 15°C and 200 g h m^{-3} above 15°C. The nominal *ct*-product below 10°C for Group 5 commodities (Annex 4.2.4) is 3600 g h m^{-3} (75 g m^{-3} x 48 hours), an excessive dose recommended to compensate for sorption and penetration so as to achieve an actual *ct*-product of about 300 g h m^{-3}. This table was produced many years ago and is used universally without taking into consideration various factors, particularly high temperatures. There is scope for revision, which may help to reduce the current dosage levels and, consequently, emissions.

Possibilities exist to reduce MeBr dosage by increasing the exposure temperatures without losing effectiveness.

Reinfestation after fumigation will cause further treatment to become necessary, possibly a further fumigation. Precautionary measures are to be taken to prevent this but the steps to be taken will vary widely according to circumstances.

Good warehouse hygiene (sanitation) is essential, including regular cleaning (preferably by vacuum cleaning) and immediate removal and burning of sweepings to reduce insect populations in stores and other structures. Insecticidal treatment of the fabric (floors and walls) of the building and the stored commodity at the time of fumigation may delay reinfestation. In some circumstances it may be possible to leave the commodity covered throughout the storage period, as done in Indonesia after CO_2 fumigation of bagged rice (Nataredja and Hodges, 1990) in order to provide a physical barrier against reinfestation. In certain cases however, the possibility of moisture migration, leading to mould development, must be taken into account.

The use of less permeable sheeting materials and better sealing of the existing structures will help to improve gas retention, and may permit fumigant application rates to be reduced and/or frequencies, particularly under tropical climatic conditions, since fumigants are more effective at high temperatures. The use of supported and unsupported laminated sheets and specially made gas proof sheets for tropical countries is to be encouraged.

A workshop was recently held in Burlingame, California, USA, to assess the state-of-the-art of methyl bromide emission reductions and research and extension priorities (Anon, 1993b). Conclusions of the workshop were that significant short-term gains in reducing emissions of methyl bromide to the atmosphere may be realised by using the following current or developing research technologies:

- Redesigned systems are needed for complete containment and recovery of methyl bromide.

- New packaging. When products are placed in packaging after fumigation the packaging material or a specific sorbent should be designed to absorb emitted methyl bromide as it desorbs from the product. If the product is fumigated in packaging, develop a package that will not absorb methyl bromide.

- Develop accurately calibrated treatments where they do not already exist, for quarantine procedures. Develop fumigation concentrations that will meet quarantine standards with methyl bromide alone or in combination with other insecticidal treatments (other fumigants, CA, etc.).

- Determine the exact fate of methyl bromide in products. Measure the quantity of methyl bromide that goes into the system, measure that which comes out and that which stays in the product or packaging material or is degraded. Determine the changes in residues on products as a result of altering exposure times versus dosages (concentrations) to reduce absorption and tailor dosages accordingly.

- Measure residual level in product and losses after fumigation. It is not possible to completely eliminate emissions from treated products. Measure loss of methyl bromide in secondary processing of treated products, for example manufacturing using methyl bromide treated logs.

Improved sealing combined with pressure testing of the enclosure prior to treatment will effectively reduce gas loss during the treatment. This will permit dosage reduction and recovery of greater proportions of MeBr.

4.2.14 Transfer of knowledge and training in improvements and alternatives

Many of the chemical alternatives to methyl bromide and non-chemical methods of treating durable commodities need further research. Information on these is either incomplete or, in certain cases, non-existent. Improved technology for sealing a fumigation area and better application methods would reduce dosages, resulting in subsequent reductions in emissions.

To disseminate acquired knowledge, key personnel should organise and attend conferences, workshops and training courses. Publications in scientific journals and bulletins will also reach personnel with similar interests. Exchanges of technical experts would be the quickest way to transfer knowledge, and sufficient funds will need to be made available for this purpose. International companies which trade in developed countries should be encouraged to increase their expenditure for training key personnel.

4.2.15 Research priorities

Note: long term: more than 10 years.

Higher Priority, Short Term

- Develop technology to reduce emissions of methyl bromide to the atmosphere.

- Develop basic biology and physiology data bases for Integrated Pest Management systems.

- Develop methods to reduce application times of controlled atmosphere treatment for quarantine use, probably in combination with high temperatures.

- Develop method(s) to discriminate between irradiated and unirradiated insects, for regulatory purposes.
- Determine available useful technologies for detection, sorting, and certification; determine feasibility and limits of the selected systems.
- Optimise controlled atmospheres; develop data on exposure times required by various atmospheres at elevated temperatures (>27°C); optimise application methods.
- Optimise hot and cold treatment methods so that the treatments are rapid and have little or no effect on quality; develop new application technologies.
- Develop commercially available microbial control agents as protectants.
- Develop insect growth regulators and formulations for long-term control.
- Develop improved packaging and containerisation technologies with special emphasis on research on practical volumes of commodities for storage, influence of environmental factors and possibilities for re-use in combination with specific insecticidal treatments.
- Develop suitable engineering components in support of priority research needs with special emphasis on problems as to scale, blending of the alternatives into systems, and designing facilities specifically for the use of alternatives.

Higher Priority, Long Term

- Develop basic biology and physiology data bases as described above.
- Develop IPM systems that provide predictable long term control using alternatives.
- Develop formulation and delivery systems for microbial control agents; concert efforts to isolate useful pathogenic micro-organisms for coleopterans; develop safety data for registration.
- Optimise large scale irradiation and heat disinfestation technologies for durables, with particular emphasis on logistic problems and minimising capital expense.

Lower Priority, Short Term

None

Lower Priority, Long Term

- Conduct surveys of natural enemies of dried fruit and nut pests for classical biological control; determine control potentials of candidate organisms; develop application methods of use; efficacy data.
- Establish control levels for mating disruption chemicals; concentrations, persistence, and formulation must be considered.
- Isolate useful genes with high expression levels for insect control by genetic engineering.

4.2.16 Uses without known alternatives

To the knowledge of this Committee, there are no uses of methyl bromide for durable commodities without potential alternatives. However, there are a number of constraints which need to be considered, and these are discussed in the following Section.

4.2.17 Constraints

Methyl bromide has been used universally for the disinfestation of post-harvest commodities for over 50 years. Due to its ease of application and effectiveness against a wide range of pest species in differing circumstances, trading nations and the trade in general did not feel any urgency to look for alternatives as methyl bromide conveniently suited their purposes. Situations such as this have certainly influenced the lack of development of other alternatives to replace methyl bromide. However, in most cases, other potential fumigants and methods do exist to supplement the use of methyl bromide.

The immediate constraints in using alternatives will be mainly technological, logistical and economic. Where alternative chemicals are used, the toxicological properties will also need to be taken into account (Annex 4.2.2). Probably a number of steps or procedures will need to be performed to replace a single methyl bromide fumigation, and these will have to be developed for each individual commodity held under different conditions. The technological innovations and economics of such procedures will have to be established before a new regimen of treatments can be introduced.

4.2.17.1 Consumer acceptance and registration of chemicals

Registration of a new chemical may take about ten years. In addition, the costs related to registration of new chemicals are extremely high (US$ 35 million or more) as full evaluations are demanded by consumers and regulators.

Although most of the insecticide applied to raw grains degrades or is removed before it reaches the consumer, residue levels in processed and unprocessed food are a sensitive issue. Tolerance levels can vary from country to country for particular materials. At an international level, an ad hoc committee examines scientific data submitted in accordance with a protocol of requirements used by the Joint FAO/WHO Meeting of Experts on Pesticide Residues (JMPR) in order to determine safe and acceptable levels of residues of chemicals in raw agricultural commodities and foods (Snelson, 1981).

Maximum levels for residues are based on experiments designed to determine the nature and level of residues resulting from the application of the chemical in accordance with good agricultural practices. The safety and acceptability of these residues is determined by comparison with extensive toxicological studies carried out on laboratory animals. Studies for carcinogenicity, mutagenicity, teratogenicity, and effects on reproduction are also required. Recommendations for maximum residue limits (MRLs) are made by the Codex Alimentarius as a result of these studies, but many countries also make their own legislation.

4.2.17.2 Technical aspects

There are technical barriers to the use of some substitutes or alternatives. Furthermore, most of the alternatives and substitutes do not have the same spectrum of activity as methyl bromide. Some may be regarded as inferior in effectiveness to methyl bromide requiring more time of exposure to be fully effective, or to be used in combination with other measures in an integrated system to give an adequate level of pest control.

Phosphine, in particular, has different properties to methyl bromide that may make it technically inappropriate as a substitute in some situations. In many situations, it is a simple alternative, and in some, it may be preferable to methyl bromide, with lower residue and taint potential.

However, it has very little activity against fungi and requires relatively long exposures to control some stages of some pests, particularly at low temperatures. Electrical equipment containing copper may be corroded and precautions must be taken to avoid flammability and explosion hazards.

Inert dusts may present another alternative useful in some particular situations. However, they require dry conditions for best effectiveness, may cause excessive wear in machinery, may give rise to dust problems in the workplace and can alter handling characteristics. Contact insecticides present an effective alternative in some situations. However, there is a possibility that particular materials may become ineffective with frequent use because of buildup of resistance by the pests. Some markets may also not accept treatments with contact insecticides.

Overall, the disadvantages of particular alternatives need to be assessed against the recognised operational disadvantages of methyl bromide, in addition to its effect on the ozone layer. These include the need for strict safety precautions to ensure worker safety and safety in the local environment, provision of gastight enclosures, lack of access to the commodity under treatment, problems of residues (excessive bromide ion) and taint on some commodities, and problems of phytotoxicity with some seeds.

Alternatives will continue to need to be assessed on a case-by-case basis, taking into account the local environment, the commodity treated, target pests, and the market and use for which the commodity is destined. Economics, logistics and engineering of installations will all need to be considered when introducing alternatives. Some promising alternatives for many durables, notably heat, cold and controlled atmospheres will need commodity- and situation-specific development, before they can be applied routinely. However, it is vital to expedite development of substitutes now. Scientists, industry and regulatory agencies need to address this issue actively.

4.2.17.3 Quarantine

There are currently very few disinfestation treatments for durable commodities which can be used for quarantine purposes and to protect them from pests at the point of importation which are as effective within the same time scale. With the alternatives now available, commodities may fail to get customs clearance resulting in reshipment or incineration, or may need much more time to disinfest to the level required by the regulatory agency.

4.2.18 References

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Case History 4.2.1: Rice Irradiation in Indonesia

1. Commodity: Rice Pest: *Sitophilus oryzae*

2. History

The Indonesian government, through its National Logistics Agency, BULOG, protects its general populace and its rice farmers against the effects of drought, floods and other natural disasters. Since an average Indonesian consumes 149 kg of raw rice per annum, BULOG buys locally produced rice to maintain the stability of rice prices and to control the market through storage of the rice for later sale and distribution. The quantity of rice stored, upwards of 2.0 million tonnes, is also sufficient to help ensure food security in an emergency. The rice is stored in 50 kg bags (6 - 9 mil polyethylene - polyester co-polymer, sewn shut). The bags are stacked seven meters high in large storage sheds. Currently the Indonesian government uses several methods to disinfest the rice: fumigation with methyl bromide, phosphine and controlled atmosphere (CO_2). With concerns about the use of chemical fumigants, and cost difficulties with controlled atmosphere, the government indicated an interest in developing another treatment.

3. Description of the alternative

Pt. Perkasa SteriGenics, a joint Indonesian and American commercial venture, operates a commercial contract irradiator in Jakarta. The facility is a modified tote/carrier - product overlap irradiator, suitable for the irradiation of a wide variety of products. A commercial efficacy test irradiation of 50 kg bags irradiated at 0.40 kGy minimum dose was conducted in 1993 and the rice was evaluated over several months for quality, the presence of weevils and other pests.

4. Regulatory agency acceptance

The irradiation of rice has been well researched and approved by the Codex Alimentarius and many other food regulatory agencies worldwide. Following the successful completion of the rice irradiation studies in Indonesia and demonstration of the scale up logistics required to commercially irradiate rice, the project was approved by the Chairman of BULOG on a limited basis.

5. Current commercial use

Commercial rice irradiation will begin in August, 1994 with 3 - 5,000 tonnes per month with the figure increasing after the 1994 harvest to 8 - 10,000 tonnes per month. Irradiation is carried out by Pt. Perkasa SteriGenics under contract to BULOG with rice storage in BULOG facilities.

6. Was the treatment difficult to develop?

Although weevils are more difficult to kill than some other pests, the dose delivered (0.40 kGy minimum) resulted in complete control of the pest at all life stages. While there was concern that the packaging material used may allow for re-infestation, it performed reasonably well in tests.

7. Was the treatment difficult to implement?

Yes. Processing substantial commercial amounts of packaged rice required sophisticated synchronisation of multiple disciplines and departments within BULOG with Pt. Perkasa Sterigenics. The success of the packaging system will continue to be evaluated and amended as required. As the projected volumes increase, the fine tuning of shipping/delivery schedules will determine the success of the facility to meet the total needs of BULOG.

8. Is the effect of this treatment on other crops being determined?

The Indonesian government through their radiation research organisation, Centre for the Application of Isotopes and Radiation, BATAN, conducts research to assess the effect of irradiation on a wide variety of products. Currently the irradiation of mangoes, strawberries and frozen shellfish are under review.

Annex 4.2.1

Table 4.2.15 Minimum exposure periods (days) required for control of all stages of the stored product pests listed, based on a phosphine concentration of 1.0 g m^{-3}. This dosage is as recommended for good conditions and the dosage applied will usually need to be increased considerably in leaky situations (EPPO 1984).

Species	Common names	Temperature	
		10 - 20°C	20 - 30°C*
Oryzaephilus surinamensis	Saw-toothed grain beetle	3	3
Cryptolestes pusillus *Oryzaephilus mercator* *Tribolium castaneum*	Flat grain beetle Merchant grain beetle Rust-red flour beetle	5	4
Lasioderma serricorne	Cigarette beetle	5	5
Acanthoscelides obtectus *Corcyra cephalonica* *Cryptolestes ferrugineus* *Plodia interpunctella* *Ptinus tectus* *Rhyzopertha dominica* *Sitotroga cerealella* *Tribolium confusum*	Dried bean beetle Rice moth Rust-red grain beetle Indian-meal moth Australian spider beetle Lesser grain borer Angoumois grain moth Confused flour beetle	8	5
Ephestia cautella *Ephestia elutella* *Ephestia kuehniella*	Tropical warehouse moth Warehouse moth Mediterranean flour moth	10	5
Caryedon serratus	Groundnut borer	10	8
Sitophilus granarius *Sitophilus oryzae* *Sitophilus zeamais* *Trogoderma granarium*	Grain/granary weevil Rice weevil Maize weevil Khapra beetle	16	8

* All species listed succumb to a 4-day exposure at this dosage level at 30°C or above.

For certain commodities in long-term storage where it is necessary to control a mite infestation two fumigations may be carried out separately by an interval dependent on ambient temperature, allowing eggs surviving the first fumigation to hatch. This interval varies from 2 weeks at 20°C to 6 weeks at 10°C (Bowley and Bell, 1981).

Annex 4.2.2

Sample toxicological data on pesticides used for treating durable commodities and structures[a,c]

Product [CAS No.]	Acute toxicity			Skin Irritation	Eye Irritation	Sensitization	Reproduction		Geno-toxicity	Oncogenicity
	LD_{50} Oral, rat (mg/kg)	LD_{50} Dermal, rabbit (mg/kg)	LC_{50} Inhalation, rat (time) (mg/m^3)				Fertility	Teratology		
Methyl bromide [74-83-9]	214(1)	ND	1173, 8h (1)	P	P	ND	I(1)	I(1)	P(1)	I(1)
Bendiocarb [22781-23-3]	40 (1)	ND	ND	ND	ND	ND	ND	ND	N (1)	ND
Boric acid [10043-35-3]	2660 (1)	ND	ND	P (1,2)	P (2)	ND	P (1)	I (1)	I (1)	N (1)
Carbon dioxide [124-38-9]	NR	NR	ND	N	N	ND	P (1)	P (1)	ND	ND
Carbonyl sulphide [463-58-1]	ND	ND	ND	ND	P (2)	P (2)	ND	ND	ND	ND
Chlorpyrifos [2921-88-2]	82 (1)	2000 (1)	>200, 4h (1)	ND	ND	ND	I (1)	ND	P (1)	ND
Copper naphthenate [1338-02-9]	2000 (1)	ND	ND	ND	ND	ND	ND	ND	ND	ND
Cypermethrin [52315-07-8]	70 (1)	>2400 (1)	7889, 4h (1)	ND	ND	ND	P (1)	ND	P (1)	ND

[a] This data was obtained from two databases only. It is unedited. Other databases and data sources, including product manufacturers and suppliers, may have other and different data. Further data may be available from regulatory agencies. This data is provided only to show the range and complexity of assessments required to give a comprehensive view of the relative toxicity of methyl bromide and alternatives. Numbers in parentheses indicate reference from which data was obtained.

[c] Abbreviations for toxicological effects:

P - Positive
N - Negative
I - Inconclusive
ND - No data available
NR - Not relevant

IARC Group definitions for oncogenicity:

- 2A:Animal - sufficient evidence
Human - limited evidence

- 2B:Animal - sufficient evidence
Human - inadequate evidence

- 3:Animal - inadequate evidence

Annex 4.2.2 (cont.)

Sample toxicological data on pesticides used for treating durable commodities and structures[a],[c]

Product [CAS No.]	Acute toxicity			Skin irritation	Eye irritation	Sensitization	Reproduction		Geno-toxicity	Oncogenicity
	LD_{50} Oral, rat (mg/kg)	LD_{50} Dermal, rabbit (mg/kg)	LC_{50} Inhalation, rat (time) (mg/m^3)				Fertility	Teratology		
Diatomaceous earth [61790-53-2]	ND	ND	ND	ND	P (2)	ND	ND	ND	ND	I IARC 3 (1)
Dichlorvos [62-73-7]	17 (1)	107 (1)	15, 4h (1)	ND	ND	ND	P (1)	P (1)	P (1)	I IARC 2b (1)
Ethyl formate [109-94-4]	1850 (1)	20,000 (1)	ND	P (1,2)	P (1,2)	ND	ND	ND	ND	ND
	rabbit: 1622 (1)	ND	ND	P (2)	P (2)	ND	ND	ND	ND	ND
Ethylene oxide [75-21-8]	72 (1)	ND	1442, 4h (1)	P (1,2)	P (1,2)	ND	P (1)	P (1)	P (1)	P (1) IARC 2A NTP-anticipated
Hydrogen cyanide [74-90-8]	mouse: 3.7 (1)	ND	176.8, 30min (1)	ND	ND	ND	ND	ND	ND	ND

[a] This data was obtained from two databases only. It is unedited. Other databases and data sources, including product manufacturers and suppliers, may have other and different data. Further data may be available from regulatory agencies. This data is provided only to show the range and complexity of assessments required to give a comprehensive view of the relative toxicity of methyl bromide and alternatives. Numbers in parentheses indicate reference from which data was obtained.

[c] Abbreviations for toxicological effects:

P	-	Positive
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ND	-	No data available
NR	-	Not relevant

IARC Group definitions for oncogenicity:

- 2A:Animal	-	sufficient evidence
Human	-	limited evidence
- 2B:Animal	-	sufficient evidence
Human	-	inadequate evidence
- 3:Animal	-	inadequate evidence

Annex 4.2.2 (cont.)

Sample toxicological data on pesticides used for treating durable commodities and structures[a,c]

Product [CAS No.]	Acute Toxicity			Skin Irritation	Eye irritation	Sensitization	Reproduction		Geno-toxicity	Oncogenicity
	LD_{50} Oral, rat (mg/kg)	LD_{50} Dermal, rabbit (mg/kg)	LC_{50} Inhalation, rat (time) (mg/m^3)				Fertility	Teratology		
Malathion [121-75-5]	290 (1)	4100 (1)	84.6, 4h (1)	ND	ND	ND	P (1)	P (1)	P (1)	I IARC 3 (1)
Nitrogen [7727-37-9]	NR	NR	ND	N	N	ND	ND	ND	ND	ND
Ozone [10028-15-6]	NR	NR	9.4, 4h (1)	ND	P (1)	ND	P (1)	P (1)	P (1)	ND
Pentachlorophenol [87-86-5]	27 (1)	ND	355[b] (1)	P (1,2)	P (2)	P (2)	ND	P (1)	P (1)	I IARC 2B (1)
Permethrin [52645-53-1]	383 (1)	>2000 (1)	685[b] (1)	P (1)	ND	ND	I (1)	ND	P (1)	I IARC 3 (1)
Phosphine [7803-51-2]	ND	ND	15, 4h (1)	ND	ND	ND	ND	ND	I (1)	ND
Propoxur [114-26-1]	70 (1)	ND	1440, 1h (1)	ND	ND	ND	ND	P (1)	P (1)	ND

[a] This data was obtained from two databases only. It is unedited. Other databases and data sources, including product manufacturers and suppliers, may have other and different data. Further data may be available from regulatory agencies. This data is provided only to show the range and complexity of assessments required to give a comprehensive view of the relative toxicity of methyl bromide and alternatives. Numbers in parentheses indicate reference from which data was obtained.

[b] No time specified

[c] Abbreviations for toxicological effects:

P - Positive
N - Negative
I - Inconclusive
ND - No data available
NR - Not relevant

IARC Group definitions for oncogenicity:

- 2A:Animal - sufficient evidence
Human - limited evidence

- 2B:Animal - sufficient evidence
Human - inadequate evidence

- 3:Animal - inadequate evidence

Annex 4.2.2 (cont.)

Sample toxicological data on pesticides used for treating durable commodities and structures[a,c]

Product [CAS No.]	Acute Toxicity			Skin Irritation	Eye irritation	Sensitization	Reproduction		Geno-toxicity	Oncogenicity
	LD_{50} Oral, rat (mg/kg)	LD_{50} Dermal, rabbit (mg/kg)	LC_{50} Inhalation, rat (time) (mg/m^3)				Fertility	Teratology		
Silica gel [7699-41-4]	ND	ND	ND	ND	P (1,2)	P (2)	ND	ND	I (1)	I IARC 3 (1)
Sodium octaborate tetrahydrate	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Sulfuryl fluoride [2699-79-8]	100 (1)	ND	4137, 4h (1)	ND	ND	ND	ND	P (1)	ND	ND

[a] This data was obtained from two databases only. It is unedited. Other databases and data sources, including product manufacturers and suppliers, may have other and different data. Further data may be available from regulatory agencies. This data is provided only to show the range and complexity of assessments required to give a comprehensive view of the relative toxicity of methyl bromide and alternatives. Numbers in parentheses indicate reference from which data was obtained.

[c] Abbreviations for toxicological effects:

P - Positive
N - Negative
I - Inconclusive
ND - No data available
NR - Not relevant

IARC Group definitions for oncogenicity:

- 2A:Animal - sufficient evidence
Human - limited evidence

- 2B:Animal - sufficient evidence
Human - inadequate evidence

- 3:Animal - inadequate evidence

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1. NTIS, 1993. Registry of toxic effects of chemical substances. Washington. Microfiche Edition, Quarterly Issue (July) (includes IARC and NTP references).
2. Lenga, R.E. (ed.) 1988. The Sigma-Aldrich Library of Chemical Safety Data. 2nd ed., Sigma-Aldrich Co. Milwaukee.

Annex 4.2.3

Table 4.2.16 Estimates of the minimum *ct*-product (g h m^{-3}) of methyl bromide for a 99.9 per cent kill of various stages of a number of insect species at 10, 15, 25 and 30°C and 70 per cent RH. (Heseltine and Thompson, 1974)

Species	Stage	Temperature (°C)			
		10	15	25	30
Callosobruchus chinensis	pre-adult stages	175	85	40	-
Cryptolestes minutus	cocoons	170	145	125	-
Ephestia cautella	pupae	-	70	55	-
Ephestia elutella	diapausing larvae	360	360	205	180
Ephestia kuehniella	pupae	-	75	60	-
Lasioderma serricorne	cocoons	-	180	100	-
Oryzaephilus surinamensis	adults	85	85	50	40
Plodia interpunctella	diapausing larvae	300	250	105	-
Ptinus tectus	cocoons	170	155	100	-
Ptinus tectus	adults	155	125	85	-
Rhyzopertha dominica	early pre-adult stages	-	40	40	-
Rhyzopertha dominica	later pre-adult stages	-	75	45	-
Rhyzopertha dominica	adults	80	65	40	-
Sitophilus granarius	early pre-adult stages	115	75	50	50
Sitophilus granarius	later pre-adult stages	200	115	65	65
Sitophilus granarius	adults	55	55	35	-
Sitophilus oryzae	pre-adult stages	-	105	85	-
Sitophilus oryzae	adults	50	30	30	15
Tribolium castaneum	pupae	-	-	125	100
Tribolium castaneum	adults	125	80	60	50
Tribolium confusum	pupae	230	180	90	-
Tribolium confusum	adults	115	85	60	45
Trogoderma granarium	larvae	290	190	110	70

(A dash in the table indicates that no test was carried out).

Annex 4.2.4

Table 4.2.17 Methyl bromide dosage table. European Plant Protection Organization (1993)

Group	Commodities	Dosage ($g\ m^{-3}$)			Exposure period (h)
		<10°C	10-20°C	>20°C	
1.	Rice, peas, beans, cocoa beans, dried vine fruits	25	15	10	24
2.	Wheat, barley, oats, maize, lentils	50	35	25	24
3.	Pollards, rice bran	70	45	30	48
4a	Sorghum, nuts, figs	75	50	35	24
4b	Groundnuts, oilseeds, dates, empty sacks	75	50	35	48
5.	Oilseeds, cakes and meals	120	85	60	48
6.	Fishmeal, dried blood etc.	140	100	65	48
7.	Flour	50	50	40	48

Notes:

1. These dosage rates apply to fumigations under gas-proof sheets and in freight containers which are usually fully loaded. If this method is to be used for mites, dosage rates should accordingly be doubled.

2. Penetration of methyl bromide into commodities in Groups 5 and 6 is poor and fumigation may be uneconomic using the recommended dosage rates. In such cases the use of phosphine should be considered and this is the preferred fumigant for Group 7 (flour).

3. To reduce the possibility of taint the dose for flour should never exceed 50 $g\ m^{-3}$.

4. Diapausing larvae of *Trogoderma granarium* (khapra beetle) and *Ephestia elutella* (warehouse moth) are highly tolerant of methyl bromide. In this case, these dosages should be increased by one half and, where applicable, exposure periods increased to 48 h in order to achieve the requisite *ct*-products.

4.3 Alternatives for treatment of perishables

Executive Summary

Perishable commodities include fresh fruit and vegetables, cut flowers, ornamental plants, fresh root crops and bulbs.

Although there are eleven different types of existing alternative treatments for disinfestation which are approved for commercial use on specific commodities, very few of the alternatives to methyl bromide studied by the Committee were found to be in commercial use. Ideally, an existing alternative is fully tested, efficacious, non-phytotoxic and economical. For example, this report shows 6 commodities have approval for disinfestation using heat, 5 using chemical treatments, nine using cold treatment, and four using pest-free zones.

When compared to methyl bromide, potential alternatives require more data showing efficacy and phytotoxicity responses. Some potential alternatives will be more commodity specific than methyl bromide requiring more research at the plant species and cultivar levels. Alternatives are generally more complex than methyl bromide which increases their costs of implementation. Potential alternatives show promise and need further research to determine their suitability for various commodities.

Currently, there are no existing alternative treatments for apple, pear, and stonefruit exports that are host to codling moth; for berryfruit; for grapes from Chile exported to the United States; and for many rootcrops that are exported to developed countries from Article 5 (1) countries.

For this reason, further international co-operation is imperative for the development of alternative treatments based on globally-accepted phytosanitary standards.

The Committee recognised methyl bromide fumigation as the predominant treatment when disinfestation is required for perishable commodities.

Using currently available estimates, about 22% of the non-feedstock methyl bromide consumed globally is used for disinfestation of both durable and perishable commodities. The percentage of this global consumption used for perishable disinfestation is estimated as 8.6%. The majority of these treatments are carried out *on arrival* in an importing country if undesirable live pests are intercepted, or occasionally *prior to export* if the importing country deems the pest to be a serious threat to their agricultural security. Some countries take a precautionary approach to meet export requirements. For example, countries sometimes fumigate perishable commodities prior to export in order to ensure their release onto the retail markets is not delayed and to avoid more expensive fumigation costs on arrival.

In a MBTOC survey of 22 industrialised and Article 5 countries, on average almost half of the tonnage of methyl bromide used on perishable commodities was for disinfestation of exported fruit. A minor quantity of methyl bromide was used to prevent the spread of pests within the same country.

Until recently there has been little perceived need to investigate alternatives to methyl bromide because it is lethal to a broad spectrum of pests, easily applied, cost-effective, and accepted by most countries. There has been, therefore, insufficient time and resources dedicated to generating scientific data to support the ability of potential alternatives to control pests without damaging the commodity. Most alternative treatments are more commodity and pest specific, require more complex equipment or procedures, and are often more expensive than methyl bromide. However, it was noted that methyl bromide does cause some injury to some products (e.g. cut flowers), and less harmful, though still effective, alternatives would be desirable.

Alternatives can be divided into those that require no postharvest treatment, and those that require either a postharvest *chemical* or *non-chemical* treatment.

Alternatives avoiding postharvest treatment

At least three countries (e.g., the United States, Japan, New Zealand) accept certain commodities certified by government officials as originating from geographically defined regions free of quarantine pests. Pest-free zones require justification through monitoring, reporting and continuous enforcement. A regulatory agency may require justification for many years because their acceptance is based on extensive knowledge of both the pest and commodity biology and phenology.

Inspection of a sample of the commodity before shipment by inspectors from the importing country, while labour intensive and relatively costly, is carried out by some countries such as those exporting to the United States, Japan and New Zealand.

The systems approach relies on preharvest management of pests in the orchard or field, followed by packhouse procedures to reject infested fruit. Generally, the pests are present in very low numbers and can be easily controlled. Preharvest control practices rarely exceed 90% pest mortality and are insufficient to comply with the predominant concept of quarantine security of greater than 99.9968% mortality. However, the desired level of security may be achieved, for example, if preharvest insect reduction practices (e.g., pesticides, pest attractants, pest resistant cultivars) are combined with packhouse sorting procedures. Systems approaches, demonstrating pest reduction from field to packed commodity, require detailed monitoring and documentation in order to be acceptable to regulatory agencies. Currently, watermelon exported from Tonga to New Zealand is the only example known to MBTOC of the systems approach in commercial practice.

Chemical alternatives

Chemical treatments using, for example, hydrogen cyanide have very limited commercial application because they are difficult to apply, have a narrow pest spectrum of activity, can severely damage many commodities, and are not approved for use in some countries. Others, such as carbon dioxide and sulphur dioxide, are at the experimental stage of development. Aerosol formulations of some plant (e.g., ethyl formate) and non-plant (e.g., dichlorvos) chemicals and immersion in dilute insecticide solutions are sometimes used on non-food, perishable exports such as cut-flowers. Apart from the difficulty of synthesising and registering a new, highly pesticidal molecule, chemical treatments are not being investigated because consumers increasingly prefer food with no pesticide residues. Registration of new chemical fumigants is also very costly (estimated to be at least US$35M) and time consuming because many countries now require extensive tests demonstrating safety to humans and the environment. Registration for this very limited postharvest use alone can take considerable time and is costly.

Non-chemical treatments

Most non-chemical treatments do not leave residues and therefore are more acceptable to consumers than methyl bromide or other chemical treatments.

The most widely used non-chemical technique is short term cold storage at -1°C to + 2°C for 10 - 15 days to kill tropical fruit flies on citrus, grapes, papaya, avocado and kiwifruit. Cold treatment is carried out commercially in-transit or using land-based facilities, and require precise records of the temperature and duration showing compliance with the phytosanitary treatment specifications in order to be acceptable as a disinfestation treatment.

Heat treatments at 40 - 50ºC for less than eight hours are also becoming more common for fruit fly control in tropical commodities, particularly those that are based on heated air rather than hot water immersion. Heat for disinfestation is being tested on some temperate commodities. The temperature, duration, and application method must be very precise to kill pests without damaging the commodity. Heat is unsuitable for highly perishable products such as asparagus, cherries or leafy vegetables as their shelf-life and marketability is reduced.

Some pests can be killed by 1 - 2 months storage at low temperatures under low oxygen/high carbon dioxide conditions (Controlled Atmosphere (CA)). The time can be reduced considerably by raising the temperature above 30ºC. However, adoption of this technology is limited mainly by inadequate data on the responses of pests and commodities to high-temperature CA and the difficulty of designing large, high-temperature, CA disinfestation facilities with adequate gas retention. Gas retention is particularly important under CA compared to gas retention with fumigants alone. There is no commercial application known to MBTOC at present illustrating the use of CA for disinfestation.

On a much smaller scale, atmospheres immediately surrounding the commodity can be modified (termed Modified Atmosphere (MA)) to kill pests using polyfilms or coatings made from wax or cellulose-based compounds. There are no commercial examples of MA for disinfestation as this treatment is under development.

Irradiation (X-rays, electron beam or isotope) can control many pest species and has additional advantages of treating the commodity in the final packaging with no appreciable change in temperature or atmosphere. Few commercial irradiators have been developed for disinfestation. Low doses are capable of achieving quarantine security by sterilising pests. Thirty five countries have approved the use of irradiation on over 50 specific food commodities including apples, banana, garlic, mango, onions, papaya, potatoes, stonefruit, and strawberries. United Nations agencies have recognised the similarity in response of fruit fly species and, in order to avoid unnecessary experiments, has recommended a minimum effective dose regardless of their host commodity. Among the factors currently influencing the adoption of this specific technology for disinfestation are widespread consumer, industry, and regulatory acceptance. Some of these factors are insufficient commercial-scale assessments of cost-benefit, verification of live but sterile pests, and perceived public concern with the safety of isotope transport, long-term storage and facility location.

Disinfestation treatments can be combined to achieve the required pest mortality. For example, cherimoya fruit exported from Chile to the USA can be treated with a mixture of soapy water and a wax coating; and lychees exported from Taiwan to Japan can be treated with vapour heat followed by a cold treatment to achieve quarantine acceptance. Combination treatments are rare, probably because of the more extensive technical documentation required to demonstrate treatment efficacy for regulatory agencies, compared with single treatment applications. However, combined treatments or procedures will, in many cases, offer greater quarantine security than a single treatment. Additionally, combined treatments may allow a reduction in the amount of methyl bromide required for pest mortality, thus reducing the potential for commodity damage and the amount released to the atmosphere.

Constraints to the development of alternatives

Alternatives have to be adapted to suit the combination of pests and commodities that occur in specific countries. Commercial implementation requires the completion of several developmental phases including laboratory experimentation, regulatory agency approval of the experimental data and proposed commercial method, engineering design and construction, and equipment certification. So far it has not been possible to completely transfer disinfestation technology between countries because each has commodities and pests that differ in tolerance to the proposed treatment and each has adopted particular phytosanitary principles. Because each potential alternative treatment must be adapted to the new country, their development requires skilled research, is labour intensive, time-consuming and costly. Commercial application typically requires from 3 to 7 years for adapting existing alternatives to a new country. Normally about 10 or more years may be needed if an entirely new quarantine treatment technology is to be developed.

Methyl bromide recycling and recovery

Because most fumigations of perishable export commodities are carried out using solid-wall fumigation facilities that retain most of the gas, there is opportunity for recovering and recycling methyl bromide. Unlike durable commodities, such as wheat, that absorb relatively large amounts of methyl bromide, perishable commodities absorb relatively little, leaving 85 - 95% available for recovery. Equipment for recovering and recycling methyl bromide requires considerable further technological development before it can be adopted widely, and is likely to be expensive.

Developing country issues

Special attention must be paid to the needs of developing countries. They are heavily dependent on technology developed in other countries. To facilitate development of alternatives, funds are required to allow researchers and quarantine personnel to attend conferences, workshops and training courses on a regular basis. Regulatory agencies in industrialised countries should review existing quarantine policies in line with international changes in phytosanitary concepts. They must ensure that clear disinfestation guidelines are made available and, if necessary, provide a technical advisor to assist with experimental design and report documentation. Opportunities for accommodating Article 5 country staff for an appropriate period of time in the laboratories of scientists developing alternative treatments should be encouraged. To ensure continuity of skilled personnel, students and quarantine officers should be encouraged at secondary and tertiary educational levels to undertake courses essential to the development and implementation of environmentally-sound alternatives.

4.3.1 Introduction

Although pesticides and other control measures are often used to kill pests in the orchard or field, these *preharvest* treatments cannot guarantee that all pests are killed. In contrast, *postharvest* disinfestation treatments are carried out under precisely controlled procedures to ensure that pests of quarantine importance are killed and not transported to other areas where they do not occur. Ideal disinfestation treatments need to be effective in controlling a broad spectrum of pests, rapid if required, non-detrimental to the commodity and the facility, safe for the operator and consumer, easily applied, environmentally sound, large scale efficiency, render the commodity safe, be cost effective, readily acceptable to the consumer and regulatory agencies.

Almost all postharvest treatments on perishable commodities are carried out for quarantine purposes. Unlike stored products where pests destroy the commodity during storage unless controlled, there is negligible damage of perishables due to pests. Considering all the disinfestation treatments currently applied in world markets, methyl bromide fumigation is by far the predominant quarantine treatment for fresh fruits, vegetables and cut flowers. Few approved quarantine treatments exist that do not use methyl bromide, and the few that do have a very narrow application (Anon., 1988, 1992).

A large number of treatment schedules has been developed to control a wide range of pests that could be present on imported fresh produce. Most countries apply a disinfestation treatment to imports if live pests are intercepted. Occasionally, the importing country requires a disinfestation treatment to be undertaken in the exporting country to control pests considered extremely damaging if accidentally imported. Any treatment developed to control pests must meet the level of quarantine security acceptable to the importing country and ensure commodity marketability.

If an alternative treatment to methyl bromide is not available, the importing country is most likely to notify the exporting country of the inability to disinfest the product on arrival if necessary, and that if quarantine pests are detected on arrival, the product will be re-shipped or destroyed. Thus, exporting countries without acceptable alternatives will face a loss of export revenue, and importing countries will not allow commodities to be imported resulting in fewer varieties of fresh commodities available for the consumer.

Section 4.3.2 quantifies methyl bromide fumigation of exported and imported perishable commodities by each country, and the amount used for those transported within the same country.

Section 4.3.3 gives a general description of alternatives to methyl bromide. Those most commonly used are discussed first. Alternatives are categorised into those that minimise pest incidence and *avoid the need* for a postharvest treatment (i.e., those based on preharvest procedures), and those that apply a postharvest *disinfestation treatment* for pest control.

Section 4.3.3.2.3 outlines the major constraints restricting the development and implementation of alternatives to methyl bromide.

Section 4.3.4 discusses examples of existing alternatives to methyl bromide currently in use for each commodity, and then describes potential alternatives with specific examples and key citations. These examples are not an exhaustive list of all those that are currently under development but rather illustrative of the range of alternatives that are under consideration. Information on research and development is being collated by a number of agencies around the world and inclusion in this chapter would require considerably more space than permissible. Commodities are grouped according to their horticultural similarity or by pests associated with them.

The key treatments and their potential uses are summarised in Section 4.3.5.

For some perishable commodities that are economically important, commercially-viable alternatives are not available to replace methyl bromide. These are listed and briefly discussed in Section 4.3.6.

For those commodities without alternatives or where alternatives are not immediately available, it will be important to reduce methyl bromide emissions as much as possible. Although emission reduction is discussed generally in Section 3.5.2, the possibilities for emission reduction for perishable commodities are highlighted in Section 4.3.7.

Sections 4.3.8, 4.3.9 and 4.3.10 highlight research priorities and the transfer of technical knowledge, particularly in relation to developing countries.

4.3.2 Existing uses of methyl bromide

Forty nine government organisations within major fruit exporting countries (listed in Annex 4.3.1) were sent forms (refer Annex 4.3.2) requesting information on the postharvest use of methyl bromide on perishable commodities.

Information was requested on:

1) Perishable commodities fumigated by the importing country as a condition of entry;

2) Perishable commodities fumigated in the country of origin before export; and

3) Perishable commodities fumigated before shipment within the same country which, for example, seeks to prevent the spread of pests from regions within a country.

Twenty-two countries replied to the survey, and their responses are shown in Annex 4.3.4 (fumigation of imports), Annex 4.3.5 (fumigation of exports) and Annex 4.3.6 (examples of fumigation for shment within the same country).

4.3.3 Characteristics of potential alternatives

This section describes 14 general alternatives or potential alternatives to methyl bromide for meeting quarantine security. Few alternative treatments have been developed for commercial use. They are more pest and commodity specific than methyl bromide, and none have all the attributes of the ideal disinfestation treatment listed. Alternative treatments may require modification to adapt them to effectively control pests without damaging the commodity. Alternative quarantine treatments typically require 3 - 7 years for adaptation under non-urgent conditions in order to complete the technical requirements. Possibly 10 or more years are needed under non-urgent conditions if an entirely new quarantine treatment is to be developed. However, the development of alternatives could be expedited by developing and adopting international standards (see Section 4.3.3.2.3 on constraints) for quarantine treatments.

Although this section lists a large number of alternative treatments, the potential for success of each treatment depends on the physiological responses of the commodity and the pests associated with each commodity. With this in mind, for each commodity grouping there are relatively few alternatives currently in use because each is developed to control one or more pests on a specific commodity, although with further research a number of potential alternatives will be developed and implemented. Until recently, there has been little impetus to develop alternatives to methyl bromide because there have been no regulatory constraints, the chemical is lethal to many pests, and it is cost-effective.

4.3.3.1 Preharvest practices and inspection procedures

The presence of pests *postharvest* indicates insufficient *preharvest* control to comply with strict phytosanitary standards, and therefore considerable attention is paid to controlling them before harvest. Inspection can be carried out to determine the effectiveness of the preharvest treatments, and if through sampling a proportion of the packed consignment the pest incidence is determined to be nil or very low, the product may be exported without a postharvest treatment. However, field control of a pest has rarely provided quarantine security. As a general rule, 90% of the pesticide applied does not hit the target pests (Luckmann and Metcalf, 1982). This results in field levels of control rarely exceeding 90% pest mortality which is an insufficient level of control for the present concept of greater than 99.9% mortality for quarantine security (Baker, 1939; Couey and Chew, 1986).

4.3.3.1.1 Cultural practices leading to pest reduction

At each stage of the commodity production and packing process, there is a reduction in pest population mainly because of the application of pesticides and sorting of pest-infested fruit by grading personnel and machinery (Mr T. Main, Manager, Aweta, Israel, pers. comm. 1994). These pest reductions can be quantified at key points in the production-to-export chain (hence the term 'Multiple Pest Decrement' or 'Systems Approach'). The systems approach is highly dependant on a knowledge of the pest/host biology and phenology. Using pest risk analyses, the probability of accidentally exporting the pest is often shown to be minimal and in some cases exceeds the level of quarantine security achieved by fumigation alone (Moffitt 1990). Provided there is no pest breeding in storage, multiple pest decrement can achieve or exceed the level of quarantine security acceptable to an importing country (Vail *et al.*, 1993). However, none has been approved as a stand-alone disinfestation treatment.

Reduction in insect populations can be achieved by cultural practises such as planting genetically modified commodities that are no longer the preferred host of the insect (host plant resistance), by harvesting when the commodity is not susceptible to attack (e.g., papaya which is harvested immature and ripened later), by harvesting when the pest is not active (e.g. diapausing or overwintering stage of the pest), by improved harvesting practices that remove 'hitchhiker pests' in the field or orchard, by the addition of biological agents such as parasitoids and predators, by releasing sterile insects, by using pheromones, or by using microbial agents as pest pathogens. However, in some cases the presence of biological and microbial agents on the commodity after harvest may cause quarantine concern.

Multiple pest decrement procedures lead to a reduction of the pests that currently occur in most horticultural production. They may substitute for a postharvest treatment if the level of quarantine security is acceptable. To date, inter-governmental agreements on multiple decrement are rare because these procedures are time-consuming, difficult to document and regulate.

4.3.3.1.2 Pest-free zones and periods

Pest-free zones have been established by some countries and consist of geographic areas where commodities may be produced and exported because of the absence of pests of quarantine importance. Japan accepts melons from the Hsingchang Uighur Autonomous Region in China based on this area being a melon fly free zone (Anon., 1988b), and Japan accepts commodities produced in Tasmania (Australia) as free from Mediterranean fruit fly (*C. capitata*) and Queensland fruit fly (*Bactrocera tryoni*) (Anon., 1989). In the future, it may also be possible for the development of pest-free periods providing importing authorities can be assured of periods when it is not possible for the pest to infest the commodity.

As no direct treatment is applied, marketability of the commodity is not impaired. However, these zones are often restricted to geographically isolated areas with buffer zones that exclude host plants and residential areas where possible, require continuous enforcement, monitoring and reporting, are based on extensive knowledge of the pest and commodity biology, and are generally expensive because of all these factors.

4.3.3.1.3 Inspection and certification

Some countries inspect a sample of the produce prior to export (termed pre-shipment inspection) and certify each consignment based on levels of acceptability for pests of quarantine importance. However, this usually does not preclude further inspection on arrival. For example, Japanese quarantine officials inspect cut flowers in the Netherlands which reduces the need for inspection and disinfestation on arrival in Japan. Some commodities are accepted only after inspection of the packed commodity and endorsement of the procedures used by the importing country to kill any live pests (e.g., Japan, United States, New Zealand), or that live pests are within permissible limits (e.g., New Zealand) (Baker *et al.*, 1990).

Inspection is environmentally acceptable but labour intensive. The costs of inspection are typically borne by the exporting country for pre-shipment certification and by the importing country for inspection on arrival. These costs may be stabilised in the future by the use of automatic inspection systems (such as low dose X-rays to "see pests", or trace detection systems to "smell pests" by detecting pest-specific chemicals) under development to individually inspect perishable commodities.

4.3.3.2 Postharvest treatments

4.3.3.2.1 Non-chemical alternatives

Non-chemical alternatives to methyl bromide are generally environmentally sound and leave commodities free of chemical residues. However, compared with methyl bromide fumigation, they require more technical expertise in their development, implementation and operation in order to kill pests without damaging the commodity.

Those treatments used commercially, or with potential for commercial use in the near future, are discussed first. Few have been accepted for quarantine use. Only heat and cold treatments for fruit fly control on papaya, mango and citrus have been commercialised to date, and extensive research is needed in most cases to commercialise other non-chemical treatments.

4.3.3.2.1.1 Cold treatment

Cold treatment is generally applied to fruit potentially infested with tropical pests which have relatively little tolerance to cold conditions compared to temperate pests. The temperature range acceptable for the use of cold treatment is typically very narrow and in addition the treatment must be documented in detail to satisfy the importing authorities. The duration and temperature of the treatment (typically - 1°C to + 2°C) depend on pest susceptibility and fruit tolerance to cold conditions. Cold treatment is particularly suitable for controlling pests found in or on some subtropical (e.g., citrus) and tropical (e.g., mangosteen) commodities providing a treatment period, usually of at least 10 days, can be accurately maintained and documented. Cold treatment is carried out in-transit or in land-based facilities. Some chilling damage can occur during treatment for some chilling-sensitive commodities. Chilling injury can be reduced if the commodity is conditioned to relatively low temperatures prior to cold storage (Houck *et al.*, 1990b). Cold treatment is used commercially for control of fruit flies in grapes, kiwifruit, and citrus (Anon., 1992).

4.3.3.2.1.2 Heat treatment

Heat treatments include those using moist (>90% relative humidity (r.h.)) or dry air (<90% r.h.), and immersion in hot water (Armstrong, 1994; Paull and McDonald, 1994). In general, heat treatments are carried out for 10 minutes to eight hours (Anon., 1992) at temperatures that range from 40 - 50°C depending on the specific temperature and duration known to be lethal to the pest. For more heat-sensitive commodities, it may only be possible to control surface pests.

Commercial shipments of tropical fruit such as mango are immersed for short periods of time in warm water at 46.1°C and above for 65 - 90 minutes to kill any pests that might be present (Anon., 1992). The water temperature and immersion period are precisely maintained so that the pest tolerance to heat is exceeded without damaging the commodity. Recently, papaya exposed to fruit centre temperatures of 47.2°C have been commercially shipped from Hawaii to the mainland USA after 4 - 7 h dry-heat (Armstrong *et al.*, 1989), or to Japan after the same exposure time to water vapour (Anon., 1972). This treatment kills all stages of 3 species of fruit fly potentially infesting this commodity. Laboratory tests are being conducted to determine the potential of water dips and water vapour treatments to kill temperate pests associated with apples, stonefruit, kiwifruit, and citrus, and the effect of these treatments on their storage life.

Heat is an environmentally acceptable but energy intensive alternative that is particularly suitable for controlling pests found in or on most tropical and some subtropical commodities. The temperature, duration, and application method must be precise to kill pests without damaging the commodity. However, heat is unsuitable for many highly perishable products such as asparagus, cherries or leafy vegetables as their shelf-life and marketability is significantly reduced by the treatment.

4.3.3.2.1.3 Controlled atmosphere

Fruit shelf-life can be extended by altering the normal atmosphere of 21% oxygen and 0.03% carbon dioxide to about 0.5 - 3% oxygen and 2 - 5% carbon dioxide, and controlling it at these atmospheres. Typically the treatments are carried out for many months at low temperatures (e.g., 0 - 2°C) and are not suitable for tropical commodities because they cause chilling injury. The exact atmosphere and temperature vary according to the fruit and variety. CAs have been widely used for at least 30 years for prolonging the storage life of apples and pears. More recently CAs have proven effective on a laboratory scale for quarantine control of temperate pests, particularly when combined for short durations with temperatures above 30°C (Whiting *et al.*, 1991). Unfortunately, in some cases the requirements for insect control damages the commodity (Smilanick, 1992).

CA is an environmentally sound treatment that is particularly suitable for controlling some pests on perishable products that store well such as apples (Batchelor *et al.*, 1983; Whiting *et al.*, 1991 for control of Lepidoptera under low and high temperature CA ; Dickler *et al.*, 1975 for low temperature control of scale insects). There are few commercial uses of CA for disinfestation of fresh products because lengthy periods in standard CA cool storage are required to achieve high pest mortality which results in an unacceptable reduction in commodity quality (Meheriuk *et al.*, 1994). Other factors limiting widespread adoption of this technology are inadequate data on the responses of pests and commodities to high-temperature CA, the difficulty of designing large high-temperature CA disinfestation facilities with adequate gas retention, and regional variation in the cost of gases for CA (Whiting *et al.*, 1991; Benshoter, 1987).

4.3.3.2.1.4 Modified atmosphere

The shelf-life of fruit can also be extended by allowing fruit respiration to modify the atmosphere, reducing oxygen and elevating carbon dioxide. The final atmosphere and the time to establish equilibrium is not easily controlled or predictable as it depends on the biological process of fruit respiration which, for example increases with increasing temperature. Modified atmospheres (MAs) are typically generated by wrapping various types of polyfilms around the commodity (Shetty *et al.*, 1989). In some cases, the commodity is palletised and wrapped, and then flushed with gases to establish the desired atmosphere. Film permeability varies with film type and temperature, making MA control difficult under the changing temperatures commodities may experience in transit. Consumers, however, may eventually limit the widespread use of this technology due to concerns with excessive use of packaging materials.

Specialised films for maintaining commodity quality using atmosphere-absorbing compounds impregnated into the film are becoming available. Such films are called 'active packaging' and are sometimes temperature activated. They are likely to be important in the future, particularly if they have a disinfestation role in addition to increasing shelf-life.

More recently, applying specialised coatings made of wax or cellulose to citrus has proven effective in the laboratory for killing Caribbean fruit fly (Greeney and McDonald, 1993; Sharp, 1990). Wax treatment of a commodity may not be acceptable to the consumer.

MA is an environmentally sound treatment that is particularly suitable for controlling pests on perishable products that can store for at least 7 days such as strawberries. However, there are currently no commercial examples of using MA for disinfestation of perishable commodities.

4.3.3.2.1.5 Irradiation

Irradiation can control many pest species and has additional advantages of allowing the commodity to be treated in the final packaging with no appreciable increase in temperature. Successful use of low dosage irradiation from isotope or electron beam sources depends on breaking the life cycle (usually resulting in sterility but sometimes mortality) of the pest without reducing the value of the commodity. Shelf-life extension occurs with only some commodities (e.g. mango, papaya, tubers, litchi and some berryfruit) at the low dosages required for disinfestation ($\leq$ 1 kGy). Considerable research on changes to commodity quality indicates irradiation is suitable for some fruits and vegetables (Anon., 1986; Kader 1986). Irradiation is an environmentally sound alternative, with more than 36 countries approving the use of irradiation on more than 40 foodstuffs including vegetables and fresh fruit (Anon., 1987).

Among the factors currently influencing the adoption of this specific technology for disinfestation are widespread consumer, industry, and regulatory acceptance. Some of these factors are insufficient commercial-scale assessments of cost-benefit, verification of live but sterile pests, and perceived public concern with the safety of isotope transport, long-term storage and facility location.

Despite these factors, many countries have approved disinfestation treatments using gamma irradiation. The internationally accepted limit for food irradiation is 10 kGy (IAEA, 1991); the United States allows treatments up to 1 kGy (Kader, 1986) to encourage its use mainly for commodity disinfestation. United Nations agencies have recognised the similarity in response of fruit fly species. In order to avoid unnecessary disinfestation experiments, they have recommended a minimum dose of 0.15 kGy which is considered effective regardless of the host commodity. Similarly, a minimum of 0.30 kGy was recommended for insects other than fruit fly and mites (ICGFI, 1989).

4.3.3.2.1.6 Microwaves

Pest control using microwaves is in the early stages of investigation. Further research is required to determine the potential of microwaves to kill pests without reducing commodity quality. This treatment may allow decentralised, on-site treatment of commodities which could be advantageous for quarantine treatment of small shipments.

4.3.3.2.1.7 Physical removal

Water under high pressure has been shown experimentally to remove large numbers of pests from the fruit surface (Honiball *et al.,* 1979 for scale insects; Yokohama and Miller, 1988 for codling moth eggs). Air under positive or negative pressure has also been used experimentally to remove pests, but not in sufficient numbers to be acceptable as a disinfestation treatment. These treatments are only suitable for removing pests on the surface of fruit such as accidental contaminants ("hitch-hikers"), scale insects and mealybugs. The choice of air or water depends on the tolerance of the commodity to the treatment or convenience of use in the packing operation.

4.3.3.2.1.8 Combination treatments

Treatments may be combined to achieve required efficacy levels. This is necessitated by the inability to achieve required efficacy levels by a single treatment, or when a single treatment causes phytotoxicity at doses required for pest control (Moffitt *et al*., 1988, 1994). For example, methyl bromide fumigation combined with a short period of cold storage kills codling moth eggs on apples more effectively than either treatment alone (Waddell, 1992). A combination of vapour heat followed by cool storage is used to kill oriental fruit flies on lychee imported from Taiwan by Japan (Anon., 1980).

The two combination treatments cited are the only known ones commercially available and accepted by regulatory agencies. The rarity of combination treatments is probably due to the extensive technical documentation required to demonstrate treatment efficacy for regulatory agencies compared with single treatment applications.

4.3.3.2.2 Chemical alternatives

4.3.3.2.2.1 Fumigation

This is the act of releasing and dispersing a pesticidal chemical so that it reaches a pest completely or partially while in the gaseous state.

Fumigation treatments using, for example, sulphur dioxide, and hydrogen cyanide depend on achieving approved concentrations, temperatures and durations to kill pests without damaging the commodity. Hydrogen cyanide may not be approved for use in all countries. Bond (1984) provides details of fumigant properties and methods of application.

Sulphur dioxide is used mainly for fungus control in cool stored grapes, and recent research has shown a potential to control mealybug and lepidopteran insects (Vail *et al.,* 1991).

Hydrogen cyanide is commonly used on fresh commodities for control of pests such as thrips, white flies, scale and aphids (Bond, 1984).

There is an interest in the use of plant volatiles such as separate applications of ethyl or methyl formate and acetaldehyde (Aharoni *et al.,* 1979; Stewart and Mon, 1984), but none are currently registered as fumigation treatments. Ethyl and methyl formate are inflammable and explosive when mixed with air at concentrations required to kill pests and may require application in an inert diluent such as CO_2. Ethyl formate is less pesticidal than methyl formate. Acetaldehyde is more effective as a fungicide than a pesticide, and its safety to humans has been questioned (Woutersen *et al.,* 1984).

Aerosol formulations using natural plant products e.g., pyrethroids, or dichlorvos insecticide, are used to kill pests on some cut flower exports in some countries such as New Zealand (Carpenter and Stocker, 1992), Australia, and Malaysia.

Fumigants generally penetrate well and are particularly suitable for killing pests that could be inside the commodity. However, they are not favoured by consumers seeking food with no pesticide residues. Registration of new chemical fumigants is also costly and time consuming as many countries now require extensive safety tests.

4.3.3.2.2.2 Chemical dips

Commodities can be dipped in a very dilute pesticide solution after harvest to kill targeted pests that might be present in or on the commodity. For example, Australian tomatoes exported to New Zealand are dipped in insecticide to control Queensland fruit fly (*Bactrocera tryoni*) (Heather *et al*., 1987) potentially inside the commodity; and some cut flowers are immersed in insecticide to control pests on the surface (Hansen *et al.,* 1992; Hata *et al.,* 1992).

Some countries discourage the use of chemical dips because of consumer concern for chemical residues, or because disposal of the pesticide solution after treatment is often environmentally unacceptable. Other countries such as New Zealand and Singapore accept the treatment providing the maximum residue limits are not exceeded. For these reasons, a chemical dip is usually acceptable on non-edible commodities such as ornamental plants, bulbs, nursery plants and cut flowers.

4.3.3.2.3 Constraints to acceptance of alternatives

The main constraints to the development and acceptance of a potential alternative quarantine treatment have been outlined in Section 2.0. Alternative treatments are developed and implemented by integrating many technical, environmental, and regulatory factors.

Economics, logistics and engineering considerations are also key factors in the acceptability of an alternative treatment.

Developing effective disinfestation treatments that do not significantly reduce commodity marketability is the most important priority. Methyl bromide often reduces the quality of many perishable commodities. The potential for acceptance of an alternative treatment should be determined by comparing the effect of methyl bromide on the commodity with the alternative, as well as the 'no treatment' evaluation. Treatment damage thresholds should be determined, particularly for sensitive commodities.

If an alternative treatment to methyl bromide is to be adopted by industry, it must be practical to apply, capable of being documented to prove that the treatment has been carried out satisfactorily, cost effective (determined mainly by equipment and operating costs), and result in an acceptable level of residues. Government approval by the importing country often requires extensive technical documentation. This step is often the major impediment to final approval of quarantine treatments.

Apart from regulatory constraints, the almost universal application and acceptance of methyl bromide for postharvest disinfestation have constrained the development of alternative treatments. For example, some regulatory agencies have a policy of only accepting 99.9968% mortality (known as Probit 9, Baker, 1939) whereas other agencies accept lower levels of mortality based on pest risk analysis (PRA) methodology. There are publications that indicate that Probit 9 mortality may not be required in order to achieve quarantine security (Landolt *et al.*, 1984, Baker *et al.*, 1990, Vail *et al.*, 1993). The use of Probit 9 security may be based largely on policy considerations rather than technical justification. Delegates to the December 1993 CODEX meeting supported PRA as a method for making phytosanitary decisions (Codex 1993). Most recently, the Food and Agricultural Organisation (FAO) has developed 'Principles of Plant Quarantine as related to International Trade' which seeks to harmonise quarantine policy between countries, and these principles will influence the development and use of alternative treatments in the future. In order to avoid loss of exports or restriction on imports due to the unavailability of a commercial alternative to methyl bromide, it is imperative that all acceptance procedures for quarantine treatments are reviewed by scientists, industry, and regulatory agencies in order to streamline the process to develop and implement alternatives as rapidly as possible.

4.3.4 Suitability of alternatives for controlling pests on each group of commodities

4.3.4.1 Apples and pears

Apple and pear exports are economically important for: Argentina, Australia, Belgium, Chile, France, Hungary, Italy, Netherlands, New Zealand, South Africa, and the United States.

Although apples and pears are infested by a large number of pests, for most countries codling moth, fruit fly, mites, scale insects and fire blight bacterial disease are the major pests of quarantine concern.

Methyl bromide has been rarely used for apples and pears, but greater amounts may be used in the near future to control codling moth on apple exports to Japan by New Zealand and the United States.

Existing alternatives: There are few commercial treatments for apples and pears to control pests. Pre-shipment certification is carried out successfully by several countries exporting to the United States including New Zealand and Chile. Cold storage with CAs have been used to kill scale insects on apples exported from Canada to California (Dickler *et al.*, 1975). USDA-APHIS approves a cold treatment to control fruit fly in apples or pears imported into the United States from Chile, France, Israel, Italy, Jordan, Mexico, South Africa, Spain, and Uruguay (Anon., 1992). Irradiation is used to increase the shelf-life of apples on a small scale in China (Xu *et al.*, 1993).

Potential alternatives: CA at low temperature kills some lepidopterous species, but shorter and more economical treatments may be achieved by combining CAs with heat, or by using heat alone. The relative tolerance of the pest compared to the commodity when exposed to CA alone, or when combined with heat, is currently being determined (Whiting *et al.*, 1992). There is an urgent need to gain a better understanding of pest and fruit physiology under CA/heat or heat alone in order to optimise treatment parameters.

A codling moth pest-free zone is feasible in Western Australia since this pest is absent in apple and pear production areas. Sterile codling moths are currently being released in the Okanagan Valley region in Canada to establish a pest-free zone (Proverbs *et al.*, 1982).

Multiple decrement is feasible, particularly as the reduction in codling moth population in apples has been documented for some packhouse operations in Washington State (Moffitt, 1990). There is potential to reduce the incidence of orchard pests by improving orchard and packhouse management practises.

The response of all stages of codling moth to irradiation has been defined (Burditt and Moffitt, 1985). 'Red Delicious' apples irradiated up to 1 kGy were marketable even after 11 months storage (Olsen *et al.*, 1989). Further research on the tolerance of apple varieties is required.

4.3.4.2 Stonefruit

Stonefruit includes peaches, plums, cherries, apricots, and nectarines. Exports are economically important for: Canada, Chile, France, New Zealand, United States, and some Mediterranean countries.

Although stonefruit are infested by a large number of pests, for most countries codling moth, fruit flies, oriental fruit moth, walnut husk fly, mites and thrips are the major pests of quarantine concern.

Some countries, e.g., United States (Yokohama *et al.*, 1987), New Zealand and Canada, have developed a mandatory methyl bromide fumigation treatment for exports of cherries and nectarines to Japan. The USDA-APHIS accepts a cold treatment alone for some stonefruit including cherries imported from Chile, plums from Israel, and apricots, peaches and plums from Morocco (Anon., 1992).

Existing alternatives: Australia has set maximum pest levels and accepts pre-shipment certification from New Zealand that these are not exceeded on nectarine and apricot exports. About 14 tonnes of fresh plums imported by South Africa from France were irradiated at 2 kGy for insect disinfestation (Mr Du Plessis, Managing Director Gammatron, South Africa, pers. comm. 1994).

Potential alternatives: Stonefruit tolerate low oxygen CAs (0.25 - 0.5% oxygen) (Kader, 1985) for 8 - 40 days depending on the commodity and the temperature. CA combined with high temperatures may damage the quality of stonefruit (Smilanick and Fouse, 1989). The potential for controlling pests under CA at a range of temperatures is currently being determined.

Preliminary research has shown some varieties of nectarines tolerated 24 hours exposure to heat using 41ºC moist air to kill some thrips species (Lay-Yee and Rose, 1994). Immersion of apricots in water heated from 25 - 45ºC for 10 - 30 minutes damaged fruit quality, probably due to inoculum in the water being carried into the core cavity of the fruit (Lay-Yee and Rose, 1994). 'Bing' cherries heated in moist air at 47ºC for 35 minutes and then stored at 0±1ºC for less than 14 days tolerated the treatment (E. Mitcham University of California (Davis) pers. comm. 1993) which may also control codling moth (Neven, 1993).

New Zealand accepts a pest-free period for walnut husk fly on nectarine exports from the United States (Yokohama *et al.*, 1992).

Cherries, nectarines and peaches are the most tolerant of all the stonefruit to irradiation and therefore this treatment offers potential for insect control. Doses up to 1 kGy did not damage 'Rainier' cherries which is approximately 3 times the dose required to kill the most tolerant stage of codling moth (Drake *et al.*, 1994).

Cherries are particularly tolerant of high carbon dioxide levels generated by a modified atmosphere treatment which may be effective for controlling pests.

Cherries and nectarines are extremely poor hosts to codling moth (Vail *et al.*, 1993; Curtis *et al.*, 1991). This fact combined with pesticides applied in the orchard and sorting in the packhouse (multiple decrement) achieves a level of security which should meet the requirements of most countries. Nectarine varieties vary in their susceptibility to field infestation levels of codling moth which suggests commodity resistance has potential (Curtis *et al.*, 1991).

4.3.4.3 Citrus

Citrus includes oranges, grapefruit, lemons, limes, tangeloes, tangerines and pummelos. Exports are economically important for: Australia, Brazil, Israel, Japan, South Africa, United States, and some other Mediterranean countries.

Although citrus are infested by a large number of pests, for most countries fruit flies, scale insects, and Fullers rose weevil are the main pests of quarantine importance.

Methyl bromide often damages citrus at concentrations required to kill fruit fly, limiting its use.

Existing alternatives: Japan accepts citrus from Florida exposed to 10 - 14 days cold treatment at 0.6ºC to control Caribbean fruit fly (*Anastraepha suspensa*); citrus from South Africa after 12 days cold treatment at -0.6ºC to control Mediterranean fruit fly (*C. capitata*); and citrus from Israel after 13 - 14 days cold treatment at 0.5ºC to control the same species. USDA-APHIS accepts cold treatment for 11 - 22 days depending on the temperature for control of fruit fly species in some varieties of citrus from 23 countries (Anon., 1992). Sometimes preconditioning at warm temperatures is necessary for citrus fruit to tolerate cold treatment (Houck *et al.*, 1990a,b; Kitagawa *et al.*, 1988). Hydrogen cyanide fumigation is used to kill scale insects. Heated *dry* air that increases the temperature of the fruit centre of grapefruit to 47.8ºC over at least a 3 hour period is an approved quarantine treatment to control Mexican fruit fly (*Anastraepha ludens*) (Anon., 1992). Heated *moist* air to a fruit centre temperature of 43.3ºC and held for 6 hours is approved for control of this pest in grapefruit, orange, and tangerine from Mexico (Anon., 1992).

Potential alternatives: These include irradiation for some varieties of oranges, grapefruit and lemons (Thomas, 1986, Johnson *et al.*, 1990). Limes exhibit significant radiation injury (Maxie *et al.*, 1969). Some citrus is individually wrapped with fungicidal film, and the modified atmosphere generated may also kill pests if insects inside the fruit do not break the film. Some MA treatments damage citrus (Houck and Snider, 1969) limiting its widespread use. Heat treatments for control of different species of fruit fly are under development for grapefruit (Sharp, 1993 in Florida; Mangan and Ingle, 1994 in Texas), and for grapefruit and 'Valencia' oranges (J.W. Armstrong, USDA-ARS Hilo pers. comm. 1993 in Hawaii). Citrus phytotoxicity as a result of heat treatment has been previously reported (Houck, 1967). There may also be opportunities for pest control by genetically inducing resistance in citrus to pests, by adding coatings to the surface of the fruit (in combination with dimethoate insecticide or heat) which reduce the ability of the internal atmosphere of the fruit to sustain pests (J.D. Hansen, USDA-ARS Miami, pers. comm. 1993), by demonstrating pest-free zones and pest-free periods, or by documenting pest reduction due to a series of control measures applied in the production of the commodity (multiple decrement). Experiments have shown high pressure water washes scale insects and Fuller's rose weevil off citrus (J.G.Morse, UC Riverside, pers. comm. 1994).

4.3.4.4 Grapes

Grape exports are economically important for: Australia, Brazil, Chile, Israel, South Africa, the United States and many European countries.

The main pests of quarantine concern on grapes are fruit flies, Lepidoptera, mealybug, and mites.

The USDA-APHIS accepts cold treatment from 30 countries for control of vine moth *Lobesia botrana* and other insects in grapes providing the treatment is combined with methyl bromide fumigation. Grape exports to the United States from Chile are accepted from a Mediterranean fruit fly free zone providing they are also fumigated with methyl bromide to control the mite *Brevipalpis chilensis*.

Existing alternatives: Japan accepts 12 days cold treatment at 0.5°C for control of Mediterranean fruit fly on grapes exported from Chile (Anon., 1990).

Potential alternatives: In-storage fumigation with sulphur dioxide (routinely applied for fungal control), alone or combined with carbon dioxide (Vota, 1957), may provide pest control, although this has received little study. Vail *et al.*, (1992) reported sulphur dioxide concentrations comparable to those used in routine fumigation of grapes killed a key insect pest in the United States. This suggests sulphur dioxide has potential to control both fungi and insects. However, the presence of sulphur residues from sulphites, typically about 10 ppm, may limit widespread use of sulphur dioxide for disinfestation. The United States requires mandatory labelling of products containing ≥ 10 ppm sulphites to warn sulphite-sensitive people of their presence. Grapes do not tolerate high concentrations of carbon dioxide for extended periods (Yahia *et al.*, 1983). Gamma radiation using < 1 kGy shows potential for disinfestation of grapes which are damaged by ≥ 1 kGy (Bramlage and Couey, 1965; Maxie *et al.*, 1971). In general the response of grapes to gamma irradiation is variable (Josephson and Peterson, 1983). Other potential alternatives requiring investigation are heat treatments, and CAs.

4.3.4.5 Berryfruit

Berryfruit includes strawberry, raspberry, blueberry and blackberry. Exports are economically important for: Australia, Brazil, Canada, Colombia, Israel, New Zealand, South Africa, the United States and Zimbabwe.

The main pests of quarantine concern are blueberry maggot and other fruit flies, thrips, aphids, and mites.

Many countries require a mandatory methyl bromide fumigation for berryfruit imported from countries with fruit flies. If fruit flies are not an issue, berryfruit are imported upon inspection. Imports of blueberries into regions in Canada that do not grow blueberries are permitted.

Existing alternatives: There are no alternatives currently available for control of internal pests. However, irradiation shows potential for controlling blueberry maggot (*Rhagoletis mendax*) in blueberries (Miller *et al.*, 1994).

Potential alternatives: Strawberries under MA of about 10% CO_2 are commercially irradiated in Florida (Marcotte, 1992) which may also allow phytosanitary control if required. Currently, strawberries are gassed with 15 - 20% carbon dioxide atmospheres (a modified atmosphere) for *Botrytis* control in-transit from California to other parts of the United States, a treatment that might also kill thrips and aphids. Fumigation with separate applications of sulphur dioxide or hydrogen cyanide may be feasible for some berryfruit crops. Heat treatments may be suitable for controlling heat sensitive pests such as thrips (Lay-Yee *et al.*, 1993), and cold treatments for control of tropical insects providing the exposure period is not detrimental to the shelf-life of the commodity. Because of the relatively short life of berryfruit, CA will not be of sufficient duration to kill pests.

4.3.4.6 Root crops

Root crops includes yams, potato, sweet potato, cassava, carrot, taro, onion, ginger, and garlic. Exports are economically important to a large number of countries, and particularly important to the national economies of many of the developing countries.

Root crops are infested by a wide range of pests including weevils , scale, beetles, thrips, mites, and nematodes. Because most of these pests can be carried in soil attached to root crops, their entry without treatment is permissible only if soil is not present. Many countries permit imports of root crops, providing the soil has been removed. Currently methyl bromide is the only registered treatment for a number of these pests on shipments of garlic and yams imported into the United States and other countries.

Existing alternatives: None known.

Potential alternatives: Irradiation is being investigated for control of the sweet potato weevil (*Cylas formicarius eleganthus*) in Florida, and in Malaysia for control of nematodes and scale (*Aspidiella hartii*) in ginger (Sidam *et al.*, 1994). Irradiation, currently used in many countries to inhibit sprouting of many root crops, could also be considered to prevent adult pest emergence. Irradiation is currently used for disinfestation of garlic in South Africa (Du Plessis, Managing Director, Gammatron, South Africa, pers. comm. 1994). Heat treatment of sweet potato is also being evaluated in Florida for control of the sweet potato weevil and the banana moth *Opogona sacchari* (Sharp, 1994).

Exposure to heat in a water dip or moist air requires evaluation because the tolerance of many root crops is unknown. Pre-shipment inspection may be possible for some root crops that are free of soil, but this will not be feasible for internal pests such as nematodes. Many of these crops can be stored for relatively long periods of time which suggests CA or cold treatments have potential for pest control. Dipping in dilute insecticide and planting pest resistant varieties may also be feasible.

4.3.4.7 Vegetables

Vegetables include green pod (e.g., long beans, french beans, peas), asparagus, broccoli, brussels sprouts; fruit-vegetables such as tomatoes; peppers; and leafy vegetables such as cabbage, cauliflower, lettuce, and spinach. Exports are economically important for a large number of countries, and particularly important to the national economies of most of the developing countries.

Vegetables are infested by a wide range of pests including fruit fly, weevils, beetles, lepidoptera, thrips, aphids and bugs. Methyl bromide fumigation is the predominant treatment when a number of these pests are detected alive on shipments imported into many countries. Some vegetables are sensitive to methyl bromide fumigation (Spitler *et al.*, 1985).

Existing alternatives: Most imports currently rely on inspection and release to the market if no live pests are intercepted. Asparagus is fumigated with methyl bromide in Japan for control of lepidoptera and mites, and with hydrogen cyanide when live thrips and aphids are intercepted. Bell peppers from Okinawa were shipped to other parts of Japan after a vapour heat treatment to control melon fly which used to infest this island. Tomatoes exported from Australia to New Zealand are immersed in a dimethoate chemical dip for control of Queensland fruit fly prior to export (Heather *et al*., 1987). Moist heated air sufficient to raise the fruit centre temperature to 44.4°C for 8.75 hours is an approved quarantine treatment for controlling *Ceratitis capitata, Bactrocera dorsalis* and *B. cucurbitae* in bell pepper and tomato imported into the United States (Anon., 1992).

Potential alternatives: Methyl or ethyl formate fumigants may control pests on leafy vegetables (Spitler *et al*., 1985). Unfortunately, effective concentrations are close to their flashpoints (Aharoni *et al*., 1979; Stewart and Mon, 1984). Further research is required to define the tolerance of the pests and commodities to these natural plant products. Environmental and/or health considerations may restrict registration of these and other biocides. Heat treatment (vapour or dip) may be feasible for some vegetables (e.g., tomato, green pod vegetables), and pests (e.g., thrips); research is required to determine the commodity and pest tolerance. Tomatoes are currently treated commercially with irradiation (Corrigan, 1993), a treatment that also appears feasible for asparagus (Markakis and Nicholas, 1972). Most leafy vegetables undergo tissue damage at doses of irradiation less than those required to kill pests (Markakis and Nicholas, 1972). Cold treatment may control tropical pests such as fruit fly in tomatoes, particularly if they are picked immature (but capable of ripening under the specific conditions) when they are more tolerant to cold storage. Cabbages are exported to Japan from New Zealand under in-transit CA conditions to maintain quality, and this treatment may have potential for controlling pests. Similarly, CA coldstorage conditions developed to maintain the quality of vegetables transported in containers from the mainland United States to Guam by the United States military were observed to kill aphids and thrips (Gay *et al*., 1994).

4.3.4.8 Cucurbits

Cucurbits include different varieties of cucumbers, melons, and squash. Exports are economically important to: Australia, Chile, Israel, Mexico, the Netherlands, New Zealand, South Africa and the United States. For some developing countries, the sale of cucurbits is very important for the national economy.

Cucurbits are infested by a wide range of pests particularly fruit fly, lepidoptera, aphids and thrips.

Most cucurbits are not fumigated with methyl bromide but are imported after inspection and certification. However, watermelon exported from Tonga to New Zealand is the only example of an intergovernmental agreement on multiple decrement, based on culling infested fruit in the field followed by fumigation with methyl bromide.

Existing alternatives: Some countries such as the United States and Japan accept imports of cucurbits only from pest free zones. Japan accepts melon from Hsingchiang region in China as this is a pest free zone for melon fly, and squash from Tasmania as this is a pest free zone for Queensland and Mediterranean fruit flies. Moist heated air sufficient to raise the fruit centre temperature to 44.4°C and held at this temperature for 8.75 hours is an approved quarantine treatment for controlling *Ceratitis capitata, Bactrocera dorsalis* and *B. cucurbitae* in eggplant, squash and zucchini (Anon., 1992).

Potential alternatives: Some cucurbits such as cucumber and squash are tolerant to heat (water or moist air), particularly if preconditioned to a temperature slightly less than the final temperature, and therefore this treatment offers potential for controlling fruit fly and lepidoptera. Preconditioning increases the tolerance of *Drosophila* to heat which may also occur with horticultural pests. Heat treatments are under development in Hawaii for eggplant and zucchini (J.W. Armstrong, USDA Hilo, pers. comm. 1993). It may be possible to develop a multiple decrement alternative since some cucurbits are not hosts to some fruit fly species, and pest-free zones may be possible for cucurbits potentially infested by melon fly in South America imported by the United States. The shelf-life of cucumber is extended by shrink wrap films, and the potential for controlling insects using this method requires further investigation (Shetty *et al.*, 1989; Jang, 1990).

4.3.4.9 Tropical fruit

Tropical fruit includes avocado, papaya, mango, banana, lychee, pineapple, guava, longan, durian, rambutan, cherimoya, carambola, passionfruit and sapodilla. Exports are economically important to: The Americas, Australia, the Caribbean, India, Indonesia, Malaysia, Mexico, Philippines, Taiwan and Thailand . For some developing countries, the sale and supply of tropical fruit is very important for the national economy.

Tropical fruit are infested by a wide range of pests including internal and external feeders, lepidoptera, mites and weevils, but fruit fly is the most predominant. Methyl bromide is not widely used on tropical commodities because the concentrations required to kill fruit fly typically exceed the tolerance of the commodity (Arpaia *et al.*, 1992, 1993).

Existing alternatives: Mango is commercially treated by *moist* heated air to raise the pulp temperature to 46.5°C for 30 minutes to control *B. dorsalis* fruit fly exported from Taiwan to Japan (Anon., 1988c, 1992). The duration and temperature requirements for mango immersed in water at 46.1°C varies from 65 - 90 minutes depending on the shape and weight of each variety (Anon., 1992). USDA-APHIS have approved treatment of papaya with dry air to a final seed cavity temperature of 47.2°C achieved over a minimum of 2 hours (Anon., 1992). This treatment for papaya is presented as the following "Case History" which summarises the development of an alternative treatment through to commercial implementation.

Cherimoya can be treated with soapy water (20 seconds in one part soap to 3000 parts water) and wax (e.g., Johnsons Wax PrimaFresh® 31 Kosher fruit coating) to control the mite species *Brevipalpus chilensis* (Anon., 1992). Papaya are treated when slightly immature, but capable of ripening later, because research has shown they are not susceptible to fruit fly infestation at this stage (commodity resistance). Similarly, avocado may be resistant to fruit fly attack when grown under well-irrigated conditions and harvested with the stems attached to the commodity (Armstrong *et al.*, 1983). Pineapple is not a host to fruit fly allowing most exports to occur after pre-shipment inspection (commodity resistance). Immature banana is accepted by Japan as free from fruit flies because even though the adults will lay eggs in them, the eggs will not hatch to form mature larvae (commodity resistance, Umeya and Yamamoto, 1971). Mango seed weevil can be controlled by irradiation at less than 0.85 kGy without phytotoxicity (Kok, 1979). Irradiation has been shown to damage avocado (Lipton *et al.*, 1967). Waxing of cherimoya for pest control is accepted for imports by the United States from Chile. Lychee imported by Japan from Taiwan are commercially treated with a combination of vapour heat and cold treatment to control oriental fruit fly (Anon., 1988d). Sub-tropical kiwifruit imported by Japan from Chile are cold treated to disinfest Mediterranean fruit fly (Anon., 1991).

Potential alternatives: Irradiation has been tested mainly on tropical fruit and shows the most potential for these commodities.

Heat (water) is effective for killing some species of fruit flies in banana, guava (Gould and Sharp, 1992), carambola (Sharp and Hallman, 1992), and mango (Sharp, 1992).

Further research is required to determine the potential of cold and heat (moist air) treatments for Hawaiian avocado. Heat treatments are under development in Hawaii for mango and lychee (J.W. Armstrong, USDA-ARS Hilo, pers. comm. 1993), and for rambutan in combination with 3% SO_2 for 60 minutes prior to heat treatment for red colour retention (R.E. Paull, University of Hawaii, pers. comm. 1993). Multiple decrement appears promising for avocado, based on pest-free zones and periods, host resistance, and host status. The germ plasm of avocado is being screened for resistance to the Caribbean fruit fly using caged adults on fruit and observing the development of eggs (J.D. Hansen, USDA-ARS Miami, pers. comm. 1993). Film wraps to control fruit fly may be feasible for papaya and other tropical fruit exports (Jang, 1990). A film wrap treatment for mangoes is under investigation. Recent experiments in Florida have shown Caribbean fruit fly are killed in grapefruit coated with NatureSeal® coating prior to heat treatments for 60 minutes at 48°C (Hallman pers. comm. 1993), and experiments are continuing on other fruit (guava, carambola and mango) and other treatments such as cold storage, irradiation, and insecticides (Hallman *et al.*, 1994).

4.3.4.10 Cut flowers and ornamentals

Cut flowers such as roses, carnations, chrysanthemums, bird-of-paradise and orchids are economically important as exports from: Australia, Colombia, Kenya, Malaysia, the Netherlands, New Zealand, Singapore, South Africa, Thailand, the United States and Zimbabwe. Ornamental exports include deciduous woody plants, evergreens, and cycads, and are also economically important as exports from these countries.

Cut flowers and ornamentals are infested by a wide range of pests including external feeders, Lepidoptera, thrips, aphids, mites and scale insects. Live pests intercepted on cut flowers and ornamentals on arrival are typically fumigated with methyl bromide (Anon., 1992). The dosage varies with temperature, target pest, and in the case of ornamentals the physiological state of the plant e.g., dormancy.

Existing alternatives: Methyl bromide is damaging to many types of cut flowers, and the most common alternative to methyl bromide is pre-clearance inspection. Some flowers and ornamentals are fumigated with hydrogen cyanide to control aphids, thrips and whitefly, but the treatment can be detrimental to some flowers such as gerbera that have a high moisture content. Hawaii and Thailand also dip cut flowers in a dilute insecticide solution such as malathion to control thrips and other pests. The USDA-APHIS approves the use of chemical dips (for about a 30 second immersion) in lieu of fumigation for those plants known to be intolerant of fumigants (Anon., 1992). Also permissible is a high-pressure water spray for *Succinea horticola* snails followed by a dilute carbaryl insecticide dip, or hand-removal of the pests where practical followed by immersion in a malathion-carbaryl dip if necessary (Anon., 1992). Aerosol formulations of insecticide chemicals (e.g., Hortigas® containing dichlorvos and Permigas® containing permethrin) are used on cut flower exports from New Zealand to Japan.

Potential alternatives: Irradiation, is being investigated further for cut flowers and their pests in several countries including the Netherlands, New Zealand, Japan, Malaysia, Philippines, and Thailand. Van de Vrie (1986) showed that cut flowers in the Netherlands could be disinfested of key pests without significantly reducing the vase life of cut flowers, and even increased the vase life of carnation, rose and freesia. Piriyathamrong *et al.*, (1986) reported that irradiation at 1.5 - 2.0 kGy controlled thrips in orchids but the vase life was about halved to 8 - 10 days.

Aerosol formulations of insecticide chemicals and natural products are under investigation in Thailand and other countries. Results to date show the formulations lack penetration into the commodity and are therefore not always kill leaf miners and mites.

Moist air heat treatment shows promise as a disinfestation treatment for tropical cut flowers and foliage (Hansen *et al.*, 1992). A proposal to control magnolia white scale (*Pseudolaucaspis cockerelli*) on anthurium using 49°C water immersion for 10 minutes will be submitted to USDA-APHIS for approval as a quarantine treatment (A.H. Hara, University of Hawaii, pers. comm., 1993).

A double insecticide dip with a 2 hour wait period between immersions has proven more effective in killing thrips species on orchids in Hawaii than a single dip. The first dip causes pest excitability, restlessness and withdrawal from cracks and crevices on the flowers. Thrips then become more directly exposed to the second immersion.

A multiple decrement approach is proving effective in controlling aphids, mealybug, thrips, earwigs and ants on red ginger in Hawaii. A postharvest insecticidal dip was only 100% effective if preharvest pesticides reduced mealybug field populations to <6%, <33% banana aphid infestation, and <70% cotton aphid infestation (Hata *et al.*, 1992).

4.3.4.11 Bulbs

Bulbs include tulip, narcissus, lily, gladiolus and garlic. Bulb exports are economically important from: China, the Netherlands, New Zealand, Taiwan and the United States.

Some bulbs e.g., narcissi, are infested by dry bulb mite, bulb mite and tulip bulb aphid, although these are often difficult to detect.

Most bulbs are currently fumigated in the United States and other countries with methyl bromide, the rate depending on whether the pest is an internal or a surface feeder. The USDA-APHIS accepts a 1 hour 43.3 - 43.9°C hot water immersion of narcissus bulbs to control *Steneotarsonemus laticeps* mite providing this is carried out within 1 month of the normal harvest date to avoid bud injury (Anon., 1992).

Existing alternatives: In Japan, bulbs infested with aphids and thrips are fumigated with hydrogen cyanide. Narcissus infested with narcissus bulb fly and thrips are dipped in hot water for 1.5 - 2 hours at 44°C.

Potential alternatives: Lillies infested with nematodes may be dipped in a dilute insecticide dip (e.g., methomyl), or for tulips infested with tulip bulb mite, in an emulsion of pirimiphos-methyl. Two-spotted spider mite and aphid are killed with dichlorvos insecticide in a aerosol formulation.

4.3.5 Summary table of existing and potential alternatives to methyl bromide for disinfestation

Summary of existing and potential alternatives to methyl bromide for disinfestation. For further details, refer to the relevant section in this chapter.

4.3.5.1. Cultural Practices (Systems Approach, Multiple Pest Decrement) (Section 4.3.3.1.1)

Existing uses:	Section
• Immature banana exported to Japan (fruit fly)	4.3.4.9
• Avocado (fruit fly)	4.3.4.9

Potential uses:	
• Apples and pears	4.3.4.1
• Cherries and nectarines to most countries	4.3.4.2
• Citrus	4.3.4.3
• Root crops	4.3.4.6
• Some cucurbits	4.3.4.6
• Avocado	4.3.4.9
• Ginger	4.3.4.10

4.3.5.2. Pest-free Zones and Periods (Section 4.3.3.1.2)

Existing uses:

	Section
• Nectarines from USA to New Zealand (walnut husk fly)	4.3.4.2
• Cucurbits to USA, Japan and some other countries (fruit fly)	4.3.4.8
• Squash from Tasmania to Japan (fruit fly)	4.3.4.8
• Melons from a region of China to Japan (fruit fly)	4.3.4.8

Potential uses:

• Apples and pears from zones that can be certified as pest-free	4.3.4.1
• Citrus	4.3.4.3
• Cucurbits from South America to USA	4.3.4.8

4.3.5.3. Inspection and Certification (Section 4.3.3.1.3)

Existing uses:

	Section
• Cut flowers from the Netherlands to Japan (many arthropod species)	4.3.3.1.3
• Apples from New Zealand and Chile to USA (codling moth and others)	4.3.4.1
• Apricots and nectarines from New Zealand to Australia (thrips)	4.3.4.2
• Curcubits from many countries (fruit fly)	4.3.4.8
• Pineapple (fruit fly)	4.3.4.9

Potential uses:

• Root crops free of soil	4.3.4.6

4.3.5.4. Cold Treatment (Section 4.3.3.2.1.1)

Existing uses:

	Section
• Apples and pears from Chile, France, Israel, Italy, Jordan, Mexico, South Africa, Spain and Uruguay to USA (fruit fly)	4.3.4.1
• Stonefruit, including cherries, from Chile to USA (fruit fly)	4.3.4.2
• Plums from Israel and Morocco to USA (fruit fly)	4.3.4.2
• Apricots and peaches from Morocco to USA (fruit fly)	4.3.4.2
• Citrus from Israel, South Africa, and Florida to Japan (fruit fly)	4.3.4.3
• Citrus varieties from 23 countries to USA (fruit fly)	4.3.4.3
• Grapes from Chile to Japan (fruit fly)	4.3.4.4
• Grapes from 30 countries to USA, in combination with methyl bromide fumigation (fruit fly, vine moth and other insects)	4.3.4.4
• Kiwifruit from Chile to Japan (fruit fly)	4.3.4.9

Potential uses:

• Berryfruit	4.3.4.5
• Root crops	4.3.4.6
• Some tropical fruit	4.3.4.9

4.3.5.5 Heat Treatments (Section 4.3.3.2.1.2)

Existing uses:	Section
• Papaya from Hawaii to Japan and mainland USA (fruit fly)	4.3.3.2.1.2
• Mango from Taiwan to Japan (fruit fly)	4.3.4.9
• Citrus shipped within the USA (fruit fly)	4.3.4.3
• Tomatoes and bell peppers to USA (fruit fly)	4.3.4.7
• Eggplant, squash, zucchini to USA (fruit fly)	4.3.4.8
• Narcissus bulbs to USA (mite) and Japan (narcissus bulb fly and thrips)	4.3.4.11

Potential uses:	
• Other stonefruit excluding cherries	4.3.3.2.1.2
• Apples	4.3.3.2.1.2
• Kiwifruit	4.3.3.2.1.2
• Anthurium flowers	4.3.4.11
• Tropical cut flowers and foliage	4.3.4.11
• Nectarines	4.3.4.2
• Bing cherries, combined with refrigeration	4.3.4.2
• Grapefruit and Valencia oranges	4.3.4.3
• Grapes	4.3.4.4
• Berryfruit	4.3.4.5
• Sweet potato and root crops	4.3.4.6
• Green pod vegetables	4.3.4.7
• Tomatoes	4.3.4.7
• Eggplant and zucchini	4.3.4.8
• Cucumber and squash	4.3.4.8
• Mango and lychee	4.3.4.9
• Banana, guava, carambola and mango	4.3.4.9

4.3.5.6 Controlled Atmospheres (Section 4.3.3.2.1.3)

Existing uses:	Section
• Apples from Canada to California (scale insects)	4.3.4.1

Potential uses:	
• Apples and pears, if combined with another treatment	4.3.3.2.1.3
• Stonefruit	4.3.4.2
• Grapes	4.3.4.4
• Root crops	4.3.4.6
• Cabbages	4.3.4.7
• Vegetables to Guam (Thrips and aphids)	4.3.4.7

4.3.5.7 Modified Atmospheres (Section 4.3.3.2.1.4)

Existing uses:	Section
• None	

Potential applications:	
• Citrus	4.3.3.2.1.4
• Cherries	4.3.4.2
• Strawberries from California to other US states	4.3.4.5
• Strawberries	4.3.4.5

• Cucurbits	4.3.4.8
• Mango	4.3.4.9
• Tropical fruit such as papaya	4.3.4.9

4.3.5.8. Irradiation (Section 4.3.3.2.1.5)

Existing uses:	Section
• Plums	4.3.4.2
• Garlic	4.3.4.11

Potential uses:	
• Apples	4.3.4.1
• Cherries, nectarines, peaches	4.3.4.2
• Some varieties of citrus	4.3.4.3
• Blueberries	4.3.4.5
• Some root crops	4.3.4.6
• Tomatoes and asparagus, but not most leafy vegetables	4.3.4.7
• Tropical fruit excluding avocado	4.3.4.9
• Some cut flowers	4.3.4.10

4.3.5.9. Microwaves (Section 4.3.3.2.1.6)

Existing uses:	Section
• None	-

Potential uses:

- Not yet determined

4.3.5.10 Physical Removal of Pests (Section 4.3.3.2.1.7)

Existing uses:	Section
• Citrus in South Africa (scale insects)	4.3.3.2.1.7
• Root crops such as potatoes, yams, carrots (wide range of soil pests)	4.3.4.6

Potential uses:	
• Citrus in the United States	4.3.4.3

4.3.5.11. Combined Treatments (Section 4.3.3.2.1.8)

Existing uses:	Section
• Cherimoya from Chile to USA, treated with soapy water and wax (mite)	4.3.4.9
• Lychee from Taiwan to Japan, treated with vapour heat and cold treatment (fruit fly)	4.3.4.9
• Certain cut flowers to USA, treated with pressurised water spray and insecticide dip (snails, insects)	4.3.4.10
• Certain cut flowers to USA, treated with hand-removal of pests and pesticide dip (thrips, aphids mainly)	4.3.4.10

Potential uses:	
• Grapefruit treated with wax coating and heat	4.3.4.9
• Mango, guava, carambola treated with wax and heat	4.3.4.9
• Citrus treated with coatings and heat or insecticide	4.3.4.3
• Rambutan treated with heat and sulphur dioxide	4.3.4.9

4.3.5.12. Fumigation (Section 4.3.3.2.2.1)

Existing uses:	Section
• Citrus treated with hydrogen cyanide (scale insects)	4.3.4.3
• Asparagus to Japan, treated with hydrogen cyanide (thrips and aphids)	4.3.4.7
• Some cut flowers treated with hydrogen cyanide (aphids, thrips, whitefly)	4.3.4.10
• Cut flowers from New Zealand to Japan, treated with aerosol formulations of pyrethroids or dichlorvos (mainly thrips)	4.3.4.10
• Bulbs to Japan, treated with hydrogen cyanide (aphids and thrips)	4.3.4.10

Potential uses:	
• Grapes, treated with sulphur dioxide alone or combined with carbon dioxide	4.3.4.4
• Some berryfruit, treated with carbon monoxide or hydrogen cyanide	4.3.4.5
• Leafy vegetables, treated with ethyl or methyl formate	4.3.4.7
• Cut flowers, treated with aerosol insecticides	4.3.4.10

4.3.5.13. Chemical Dips (Section 4.3.3.2.2.2)

Existing uses:	Section
• Tomatoes from Australia to New Zealand (fruit fly)	4.3.4.7
• Cut flowers from Thailand and Hawaii (thrips and other pests)	4.3.4.10

Potential uses:	
• Root crops	4.3.4.6
• Some tropical fruit	4.3.4.9
• Lilies, orchids, tulips	4.3.4.10

4.3.6 Commodities without approved quarantine alternatives to methyl bromide

Although there are many potential alternatives, currently there are no approved postharvest quarantine treatments to replace methyl bromide for the following commodities that have mainly internal feeding pests. In rare cases, however, export of these crops is carried out without methyl bromide treatment under agreements that allow pre-shipment certification. If a pest is detected, methyl bromide is currently the only approved treatment.

- Apple exports potentially infested with codling moth to countries free of codling moth. This is important for New Zealand and the United States exports to Japan.

- Stonefruit (peaches, plums, cherries, apricots, nectarines) exports potentially infested with codling moth to countries free of codling moth.

- Grapes from Chile potentially infested with *Brevipalpis chilensis* mite on exports to the United States.

- Berryfruit (strawberry, raspberry, blueberry and blackberry). Exports are economically important for the United States, New Zealand, Colombia, Australia, Israel, Brazil, South Africa, Canada, and Zimbabwe.

- Root crops (carrot, cassava, garlic, ginger, onion, potato, sweet potato, taro, and yams). Some of these crops are exported in minor (but often economically significant) volumes from developing countries to ethnic groups in developed countries.

4.3.7 Opportunities to reduce emissions

Postharvest disinfestation of perishable commodities using methyl bromide is carried out in fixed-wall structures such as a fumigation chambers, or under gastight tarpaulins.

Controlled conditions allow manipulation of the key fumigation parameters: dosage, temperature and time. Greater control is potentially more achievable in an enclosed structure. The dosage can be reduced by increasing either the temperature or the time, or both. Forced air circulation could also allow reduction of the dosage. Methyl bromide could be conserved by developing high temperature schedules with or without longer fumigation durations, providing the marketability of the produce is acceptable.

Improving the gas tightness of fumigation facilities will prevent unwarranted leakage of methyl bromide into the atmosphere. Simple test criteria have been provided to the industry for determining the gas tightness of chambers (Bond, 1984, see also Section 3.5).

More accurate measuring equipment (weighing scales, and measuring cylinder with dispenser) will minimise excessive use of methyl bromide. This equipment could also be attached for fumigation from small cylinders (e.g., 5 kg) which would avoid the use of small cans (about 1 kg).

A combination of gases e.g., methyl bromide with carbon dioxide and phosphine, allows a reduction in methyl bromide, is less phytotoxic to cut flowers and ornamentals than methyl bromide or phosphine alone, and has the same insecticidal activity (Anon., 1994).

Currently, most fumigation chambers release methyl bromide into the atmosphere at the end of the fumigation period. Equipment currently under development to recover methyl bromide could be attached to the fumigation chamber, making up to about 80% of the gas available for the next fumigation depending on commodity adsorption and losses to the facility (see Section 3). However, the use of such systems will depend mainly upon the level of emission reduction required, and, in the absence of legislation, to some extent on the cost-benefit of methyl bromide recovery and recycling.

4.3.8 Research priorities

The research priorities for alternatives to methyl bromide are different for developing and developed countries because each has different market requirements and economic constraints.

4.3.8.1 Developing countries

Developing countries are largely dependent on technology tested and available in other countries. Assistance should be provided by developed countries for the implementation of specific alternatives. For example, a heat treatment for papaya was developed in the United States (Armstrong *et al.*, 1989) and modified by New Zealand for use in the South Pacific (Waddell *et al.*, 1993). This process is now used on Cook Island papaya exports, replacing ethylene dibromide which was recently banned. The project was financed by a consortium of government and private organisations.

The choice of alternatives will be determined largely by the commodity tolerance, the target pest, and the potential for success based on previous research findings. Most research in developing countries currently involves heat treatments. There is also some research on irradiation for high value fruit exports because most tropical commodities have been shown to tolerate these treatments.

Currently, grapes exported from Chile to the USA, and cut flowers (roses, carnations and statice) exported to Europe, USA, Scandinavia and Japan are the only examples of commodities from a developing country with no alternative treatment.

4.3.8.2 Developed countries

Most research involves the development of heat, cold, CA, MA and combinations of these alternatives in the short term because these have shown the most potential for many commodities. Treatments based on preharvest procedures (inspection, pest-free zones and periods, and multiple decrement) are also high priority, but are longer term since considerable documentation on pest security is required by regulatory agencies. Irradiation research is usually given medium priority as scientific information on the effects on the commodity and the pest is generally recognised as sufficient, although high priority is given if other alternatives are less promising.

Those commodities with no potential alternative treatment currently available are apples and stonefruit exports to Japan, and rootcrops with unacceptable pest levels upon importation into many countries. Therefore these commodities should have a high priority for research.

4.3.9 Transfer of knowledge, and training in improvements and alternatives

Funds are required for key personnel to attend conferences, workshops and training courses. Information on postharvest alternatives must be written in the appropriate technical language and published in scientific journals and bulletins.

Developing countries should request clear guidelines for the development of disinfestation treatments. A technical expert from the developed country may be necessary to assist with experimental design (including equipment, lifestages, commodity quality) and report documentation necessary for demonstrating quarantine security. Ongoing exchange visits to developing countries by scientists and technicians are essential for effective collaboration in projects that test and implement alternatives.

To ensure continuity of skilled personnel, quarantine officers and students should be encouraged to undertake courses essential to the development and implementation of alternatives, particularly those related to plant physiology, entomology, engineering and related areas. International companies with facilities in developing countries should be encouraged to increase their technology transfer expenditures.

4.3.10 Developing country issues

Postharvest treatments using methyl bromide are more common for perishable commodities exported from developing countries in Asia and Latin America than Africa which, apart from Kenya and Zimbabwe, has relatively few such exports. Methyl bromide is mainly used to disinfest cut flowers, vegetables and fruit in Asia and Latin America.

Despite this varying usage, developing countries have similar requirements that include:

- Obtaining the appropriate disinfestation technology;
- Transferring this technology to the local environment;
- Training personnel to carry out new disinfestation treatments;
- Obtaining sufficient funds to allow completion of the research to demonstrate efficacy; and
- Training in the commercial use of alternatives.

Ideally, any alternative treatment to methyl bromide must be appropriate to the local conditions, i.e., cost-effective, safe to apply, environmentally sound, simple to use, and require minimal maintenance. Promising technologies must be tested in the developing countries. Highly skilled personnel are required to adapt the technology to the local conditions, train local staff in its effective use, and develop treatment and operational manuals in collaboration with technical staff.

The first priority must be to replace methyl bromide with an alternative treatment. However, if this is not possible, an interim strategy must be to reduce the amount of methyl bromide released to the atmosphere. This could be achieved by fitting fumigation facilities with recovery equipment as soon as it becomes commercially available. Equipment for recovering and recycling methyl bromide requires further technological development before it can be adopted widely, and it is likely to be expensive.

4.3.11 References

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Case History 4.3.1: Heat Disinfestation Treatments for Papaya in Hawaii

1. Commodity:

Papaya, *Carica papaya* L.

Pests:

Mediterranean fruit fly, *Ceratitis capitata* (Widemann)
Melon fly, *Bactrocera cucurbitae* (Coquillett)
Oriental fruit fly, *Bactrocera dorsalis* (Hendel)

2. History

Quarantine disinfestation treatments are required for the export of papaya from Hawaii because of the presence of tephritid fruit flies. When ethylene dibromide was banned in the U.S.A. in 1984, interest in heat treatments resulted in the development of hot-water immersion, vapour heat (VH), and high-temperature forced-air (HTFA) treatments. The hot-water immersion treatment is no longer used, but the HTFA and VH treatments are still in use today. HTFA and VH treatments are essentially the same treatment except that humidity is held low or the dew point of the air is held below the dew point of the fruit to preclude condensation on the fruit surface during HTFA treatment. The fruit surface is wet during VH treatment and dry during HTFA treatment.

3. Description of the alternative

Methyl bromide (MeBr) fumigation was tested as an alternative quarantine treatment, but it caused excessive damage (phytotoxicity) to the fruit at ambient temperatures. Further research found that if papayas were heated to 30ºC, the fruit would tolerate MeBr fumigation. Furthermore, high-temperature fumigation permitted reductions in both MeBr concentration and fumigation time while still provide quarantine security. However, with the availability of HTFA and VH treatments, high-temperature MeBr fumigation was never used commercially.

4. Regulatory agency acceptance

VH treatment of papaya in Hawaii was accepted by the U.S.A. Department of Agriculture, Animal and Plant Health Inspection Service during the 1970s, and by Japan Ministry of Agriculture, Fisheries and Forestry in the mid-1980s. HTFA treatment was accepted by USDA, APHIS in 1988. The hot-water immersion treatment was accepted by USDA, APHIS in 1985, then rescinded in 1991 because of regulatory difficulties with the treatment.

5. Current commercial use

Tropical Hawaiian Products, Inc.; Pacific Tropical Products, Inc.; and Diamond Head Papaya Co. Inc., of Hilo, Hawaii, treat all export papayas with either HTFA or VH treatment. In the past three years papaya exports in excess of approximately 60,000 tons were treated with either HTFA or VH treatment.

6. Was the treatment difficult to develop?

Yes. The time and temperature combinations required kill fruit fly eggs and larvae to provide quarantine security are close to the conditions that will cause heat-induced damage to the fruit.

7. Was the treatment difficult to develop?

Yes. Engineering problems were encountered when scaling up from laboratory research to the commercial situation; and the regulatory certification and monitoring commercial equipment presented difficulties.

8. Is the effect of this treatment on other crops being determined?

Yes. HTFA and/or VH disinfestation treatments are in use or being researched for atemoya, avocado, carambola, capsicums, citrus, cucumber, eggplant, green beans, guava, mango, and zucchini. Hot-water immersion treatments are in use or being researched for carambola, guava, litchi, mango, and sapote.

Annex 4.3.1

Table 4.3.1 List Of Countries That Were Sent Forms to Determine the Postharvest Use of Methyl Bromide on Perishable Commodities

Argentina
Australia
Belgium
Bolivia
Brazil
Canada
Chile
China
Colombia
Costa Rica
Cuba
Denmark
Dominican Republic
Ecuador
Egypt
Fiji
France
Germany
Greece
Guatemala
Honduras
Hungary
India
Indonesia
Israel
Italy
Ivory Coast
Japan
Republic of Korea
Malaysia
Mexico
Morocco
New Zealand
Panama
Philippines
Poland
Saudi Arabia
Singapore
South Africa
Spain
Sweden
Switzerland
Thailand
The Netherlands
Turkey
United Kingdom
United States of America
Uruguay
Venezuela

Annex 4.3.2

Forms Sent to Government Organisations Within Each Country to Determine the Postharvest Use of Methyl Bromide on Perishable Commodities

United Nations Environment Programme

Methyl Bromide Technical Options
Committee

«DATA MBTOC Disk #1:Info on world MB use:MB Form addresses»

File H2/5/11/6

May 20, 1993

«address»

Dear «IF name»«name»«ELSE»Sir/Madam«ENDIF»,

Re: 1993 United Nations Environment Programme (UNEP) Methyl Bromide Technical Options Committee (MBTOC)

Methyl bromide is a gas of world-wide economic importance. Its use as a postharvest fumigant to control pests on fresh fruit, vegetables and cut flowers is often essential for export earnings from horticulture for many countries.

This fumigant was recently identified as a substance that depletes the stratospheric ozone layer. Depletion of the ozone layer causes skin cancer, cataracts, suppression of the human immune system, damage to agricultural crops, as well as other adverse environmental effects.

The United Nations Environment Programme (UNEP) has recently established a Methyl Bromide Technical Options Committee (MBTOC) to evaluate the technical and economic feasibility of reducing and phasing out the world wide production of methyl bromide. The MBTOC is chaired by Dr H. Jonathon Banks, CSIRO Canberra, Australia.

Prior to the meeting of the Open-ended Working Group of the Parties to the Montreal Protocol, and the Seventh Meeting of the Parties to the Montreal Protocol, the MBTOC must submit a report to the Secretariat evaluating the technical and economic feasibility of reducing and phasing out the world-wide production of methyl bromide. The Montreal Protocol on substances that Deplete the Ozone Layer is the international agreement that controls the production and consumption of ozone-depleting substances such as chlorofluorocarbons (CFC's) used as refrigerants

The Protocol list of controlled substances was recently amended to include methyl bromide. This amendment was based in part on a "Methyl Bromide Science Workshop" (Washington DC June 2-3 1992) which was a scientific assessment of the atmospheric impact of methyl bromide, and the results of an "International Workshop on Alternatives and Substitutes for Methyl Bromide" (Washington DC, 16-18 June 1992).

This first MBTOC meeting was held in the Hague, Netherlands, 25-29 March 1993. It was mainly organisational and discussed the report structure, subcommittee involvement, work programmes, and timetable. At this meeting, a subcommittee on "Perishable Commodities" was formed to determine the postharvest use of methyl bromide on perishable commodities.

This letter requests your assistance for determining the postharvest use of methyl bromide on perishable commodities. Three forms (fumigation of exports, imports, and fumigation of commodities for shipment within your country) are attached to enable you to provide this information as completely as possible, and a fourth form relates to methyl bromide fumigation facilities and recovery equipment. Please photocopy the second page of the first three forms if you require additional space. «IF english="N"»Please excuse us for sending this in English, but we do not have funds to translate this into your language. «ENDIF»Handwritten (but legible) replies are acceptable«IF english="N"», preferably in English«ENDIF».

This form must be completed and returned to Mr Akio Tateya at the address given below no later than 20 June 1993. The information from your country will be collated with information from other countries in early July, and presented at a meeting of MBTOC in mid-July 1993.

Please confirm by fax to Tom Batchelor (+64 9 815 4201) upon receipt of this letter that you are able to complete this form by no later than 20 June 1993. If you are not able to complete this form, please suggest to Tom Batchelor the best person (address, telephone and facsimile) or Department within your country that will be able to assist.

We are fully aware that our request for your assistance is yet another demand on you time. However, we depend very heavily on your input, and we thank you very much in advance. We look forward to hearing from you.

Yours sincerely,

Akio Tateya

Thomas A. Batchelor
Science Manager

Akio Tateya
Head of Planning and Coordination Section

Enclosures:

Form 1: Fumigation of Imports
Form 2. Fumigation of Exports
Form 3. Fumigation of commodities for shipment within the same country
Form 4: Methyl bromide fumigation and recovery facilities
List of fresh fruit commodities
List of fresh vegetable commodities
List of cut flowers and ornamentals
List of bulbs and tubers
List of nursery plants

Perishables Sub-Committee Chairs:

Dr Thomas A. Batchelor, The Horticulture and Food Research Institute of New Zealand Ltd., Mt. Albert Science Centre, Private Bag 92 169, Auckland, NEW ZEALAND.
(Ph: +64-9-849 3660, Fax: +64-9-815-4201 if more than 2 pages; Fax: +64-9-815 4217 if less than 2 pages)

Mr Akio Tateya, Yokohama Plant Protection Station MAFF, 6-64 Kitanakadori Naka-ku, Yokohama 231, JAPAN.
(Ph: +81-45-211 2294, Fax: +81-45-201 2360)

FORM 1: FUMIGATION OF IMPORTS

Methyl bromide use on fresh products at the port of entry into your country

Country:	Address:	Telephone Number:
Contact person:		Facsimile Number:

Please list the fresh commodities fumigated with methyl bromide at the port (sea, air) of entry in you country (see attached list)	Methyl bromide dose, duration and temperature	Target pest(s)[1] class e.g., mites, lepidoptera, fruit fly etc	Origin by country (percent) in 1992, as a proportion of total imports for this commodity	Volume imported (1992) as pieces, Kg, tons, or tonnes	Percentage of this commodity fumigated with methyl bromide[2]	Approximate amount of MB used (tons, tonnes, Kg) for this commodity in 1992	Estimated value of commodity treated with methyl bromide in 1992 (US$)
e.g., Asparagus	$48gm^{-3}$/2 hrs/15-25°C	Lepidoptera	Australia (30%), USA (40%), Tainwan (10%)	2,000 tons	30%	3,500 Kg	$200,000

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[1] Target pests are described as major pests for their class

[2] If this is not available for individual commodity, please list the amount as a group e.g., fresh fruits and vegetables

FORM 1: FUMIGATION OF IMPORTS

Please list the fresh commodities fumigated with methyl bromide at the port (sea, air) of entry in you country (see attached list)	Methyl bromide dose, duration and temperature	Target pest(s)[3] class e.g., mites, lepidoptera, fruit fly etc	Origin by country (percent) in 1992, as a proportion of total imports for this commodity	Volume imported (1992) as pieces, Kg, tons, or tonnes	Percentage of this commodity fumigated with methyl bromide[4]	Approximate amount of MB used (tons, tonnes, Kg) for this commodity in 1992	Estimated value of commodity treated with methyl bromide in 1992 (US$)

---

[3] Target pests are described as major pests for their class

[4] If this is not available for individual commodity, please list the amount as a group e.g., fresh fruits and vegetables

FORM 2: FUMIGATION OF EXPORTS

Methyl bromide use on fresh EXPORT products after harvest by your country

Country:	Address:	Telephone Number:
Contact person:		Facsimile Number:

Please list the fresh commodities fumigated with methyl bromide after harvest in your country (see attached list)	Methyl bromide dose, duration and temperature	Target pest(s)[1] class e.g., mites, lepidoptera, fruit fly etc	Export destination by country in 1992	Volume exported (1992) as pieces, Kg, tons, or tonnes	Percentage of income from horticultural exports for your country for this commodity	Estimated volume to be exported in year 2000 from your country	Quantity of MB used (tons, tonnes, Kg) for this commodity in 1992
e.g., Onions	$48gm^{-3}$/2 hrs/15-25°C	Lepidoptera	Australia (30%), USA (40%), Tainwan (10%)	2,000 tons	30%	3,500 tons	2 tons

---

[1] Target pests are described as major pests for their class

FORM 2: FUMIGATION OF EXPORTS

Please list the fresh commodities fumigated with MB after harvest in your country (see attached list)	Methyl bromide dose, duration and temperature	Target pest(s) class e.g., mites, lepidoptera, fruit fly etc	Export destination by country in 1992	Volume exported (1992) as pieces, Kg, tons, or tonnes	Percentage of income from horticultural exports for your country for this commodity	Estimated volume to be exported in year 2000 from your country	Quantity of MB used (tons, tonnes, Kg) for this commodity in 1992

FORM 3: Methyl bromide use on fresh commodities after harvest and shipped within your country

Country:	Address:	Telephone Number:
Contact person:		Facsimile Number:

Please list the fresh commodities fumigated with methyl bromide after harvest and shipped within your country (see attached list)	Methyl bromide dose, duration and temperature	Target pest(s)[1] class e.g., mites, lepidoptera, fruit fly etc	Shipped from...to... e.g., name the regions or states	Volume shipped (1992) as pieces, Kg, tons, or tonnes	Value of this commodity as a percentage of total horticultual products for your country	Estimated volume to be shipped in year 2000 within your country	Quantity of MB used (tons, tonnes, Kg) for this commodity in 1992
e.g., Onions	$48 gm^{-3}$/2 hrs/15-25°C	Lepidoptera	Region 'A' to Region 'B'	2,000 tons	5%	3,500 tons	2 tons

---

[1] Target pests are described as major pests for their class

FORM 3: Methyl bromide use on fresh commodities after harvest and shipped within your country

Please list the fresh commodities fumigated with methyl bromide after harvest and shipped within your country (see attached list)	Methyl bromide dose, duration and temperature	Target pest(s)[2] class e.g., mites, lepidoptera, fruit fly etc	Shipped from...to... e.g., name the regions or states	Volume shipped (1992) as pieces, Kg, tons, or tonnes	Value of this commodity as a percentage of total horticultual products for your country	Estimated volume to be shipped in year 2000 within your country	Quantity of MB used (tons, tonnes, Kg) for this commodity in 1992

---

[2] Target pests are described as major pests for their class

Annex 4.3.3

Perishable commodities treated with methyl bromide, at least on some occasions, for disinfestation and pest control

FRESH FRUIT

- Apple
- Apricot
- Banana
- Blackberry
- Blueberry
- Cactus pear (prickly pear)
- Cerimoya
- Cherry
- Citrus
  - Orange
  - Grapefruit
  - Lemon
  - Lime
  - Others
- Coconut
- Durian
- Feijoa
- Grape
- Guava
- Kiwifruit
- Longsat
- Loquat
- Lychee (Litchi)
- Mango
- Melons
  - Cantaloupe
  - Honeydew
  - Muskmelon
  - Watermelon
  - Others
- Nectarine
- Olive
- Papaya
- Passionfruit
- Peach
- Pear
- Persimmon
- Pineapple
- Plum
- Pomegranate
- Quince
- Raspberry
- Sapodilla
- Starfruit
- Strawberry
- Tamarind

Annex 4.3.3 (cont.)

Perishable commodities treated with methyl bromide, at least on some occasions, for disinfestation and pest control

VEGETABLES

- Arrowhead
- Artichoke
- Asparagus
- Basil
- Beet
- Bell pepper
- Broccoli
- Brussel sprout
- Cabbage
- Carrot
- Cassava
- Cauliflower
- Celery
- Celtuce
- Chayote
- Chervil
- Chicory
- Chinese cabbage
- Chinese leek
- Chrysanthemum (edible leafy vegetable)
- Coriander
- Corn (fresh)
- Cress (garland, garden, winter)
- Cucumber
- Dandelion
- Dasheen
- Dill
- Edible burdock
- Eggplant
- Endive
- Fennel
- Garlic
- Ginger
- Green pod vegetables
  - Broad bean
  - Kidney bean
  - Soybean
  - Pea
  - Others
- Horseradish
- Indian rice (wild rice)
- Leek
- Lettuce
- Lotus
- Okra
- Onion
- Parsley
- Parsnip
- Peppermint
- Plantain
- Potato
- Pumpkin
- Purslane
- Rhubarb
- Sorrel
- Spinach
- Squash
- Sweet potato
- Swiss chard
- Tomato
- Yam
- Zucchini

Annex 4.3.3 (cont.)

Perishable commodities treated with methyl bromide, at least on some occasions, for disinfestation and pest control

CUT FLOWERS and ORNAMENTALS

Acacia	*Acacia* spp.
Adenanthos	*Adenanthos* spp.
Agapanthus	*Agapanthus* spp.
Alstroemeria	*Alstroemeria* spp.
Anigozanthus	*Anigozanthus* spp.
Banksia	*Banksia* spp.
Berzelia	*Berzelia* spp.
Boronia	*Boronia* spp.
Brunia	*Brunia* spp.
Butcher's Broom	*Ruscus* spp.
Calathea	*Calthea* spp.
Calla	*Zantedeschia* spp.
Canada Tree	*Gaultheria* spp.
Carnation	*Dianthus caryophyllus*
Chrysanthemum	*Chrysanthemum* spp.
Coco Palm	*Cocos* spp.
Douglas Fir	*Pseudotsuga* spp.
Dracaena	*Cordyline* spp.
	Dracaena spp.
Eryngium	*Eryngium* spp.
Eurya	*Eurya* spp.
Everlasting	*Helichrysum* spp.
Fern	
Club-moss	*Lycopodium* spp.
Davallia	*Davallia* spp.
Nephrolepsis	*Nephrolepsis* spp.
Polystichopsis	*Polystichopsis* spp.
Rumohra	*Rumohra* spp.
Fir	*Abies* spp.
Freesia	*Freesia* spp.
Galax	*Galax* spp.
Gladiolus	*Gladiolus* spp.
Galingale	*Cyperus* spp.
Gypsophila	*Gypsophila* spp.
Heath	*Erica* spp.
Heliconias	*Heliconia* spp.
Japanese Cleyera	*Cleyera* spp.
Juniper	*Juniperus* spp.
Larkspur	*Delphinium* spp.
Leucosperumum	*Leucospermuμ* spp.
Lily	*Lilium* spp.
Nerine	*Nerine* spp.
Orchid	*Orchidaceae*
Ornithogalum	*Ornithogalum* spp.
Phaenocoma	*Phaenocoma* spp.
Prairie Gentian	*Eustoma* spp.
Protea	*Protea* spp.
Sandersonia	*Sandersonia* spp.
Scholtzia	*Scholtzia* spp.
Screw-Pine	*Pandanus* spp.

Annex 4.3.3 (cont.)

Perishable commodities treated with methyl bromide, at least on some occasions, for disinfestation and pest control

CUT FLOWERS and ORNAMENTALS (cont.)

Sea-Pink	*Limonium* spp.
Shell Ginger	*Alpinia* spp.
Silver Tree	*Leucadendron* spp.
Summer Cypress	*Kochia* spp.
Tail Flower	*Anthurium* spp.
Verticordia	*Verticordia* spp.
Waxflower	*Chamelaucium* spp.

BULBS, TUBERS, etc.

African corn lily	*Ixia* spp.
Amaryllis	*Hippeastrum* spp.
Calla	*Zantedeschia* spp.
Christmas bell	*Sandersonia* spp.
Crocus	*Crocus* spp.
Freesia	*Freesia* spp.
Fritillary	*Fritillaris* spp.
Giganteum	*Allium giganteum*
Garlic	*Allium sativum*
Gladiolus	*Gladiolus* spp.
Hyacinth	*Hyacintus*
Iris	*Iris* spp.
Lily	*Lillium* spp.
Lycoris	*Lycoris* spp.
Narcissus	*Narcissum* spp.
Shallot	*Allium ascalonicum*
Tufted Stone Leek	*Allium fistulosum* var. *caepitosum*
Tulip	*Tulipa* spp.
Unifolium	*Allium unifolium*

Annex 4.3.3 (cont.)

Perishable commodities treated with methyl bromide, at least on some occasions, for disinfestation and pest control

NURSERY PLANTS

Aechmea	*Aechmea* spp.
Alchemilla	*Alchemilla* spp.
Alstroemeria	*Alstroemeria* spp.
Anigozanthus	*Anigozanthus* spp.
Asarum	*Asarum* spp.
Bermuda Grass	*Cynodon dactylon*
Billbergia	*Billbergia* spp.
Carnation	*Dianthus caryophyllus*
Cherimoya	*Annona cherimoya*
Chrysanthemum	*Chrysanthemum* spp.
Cinquefoil	*Potentilla* spp.
Coco Palm	*Cocos* spp.
Croton	*Croton* spp.
Cryptanthus	*Cryptanthus* spp.
Cucumber Tree	*Magnolia* spp.
Day-Lily	*Hemerocallis* spp.
Dogwood	*Cornus* spp.
Dracaena	*Cordyline* spp. *Dracaena* spp.
Evening Primrose	*Oenother* spp.
Fauwort	*Cabomba* spp.
Fig-Tree	*Ficus* spp.
Geranium	*Geranium* spp.
Guzmania	*Guzmania* spp.
Hawthorn	*Crataegus* spp.
Holly	*Ilex* spp.
Honeysuckle	*Lonicera* spp.
Hydrangea	*Hydrangea* spp.
Ivy	*Hedera* spp.
Ivy-Arum	*Scindapsus* spp.
Juniper	*Juniperus* spp.
Lilac	*Syringa* spp.
Maidenhair Fern	*Adiantum* spp.
Maple	*Acer* spp.
Michelia	*Michelia* spp.
Neoregelia	*Neoregelia* spp.
New Jersey-Tea	*Ceanothus* spp.
Orchid	*Orchidaceae*
Pachira	*Pachira* spp.
Pampas Grass	*Cortaderia* spp.
Polygonum	*Polygonum* spp.
Polyscias	*Polyscias* spp.

Annex 4.3.3 (cont.)

Perishable commodities treated with methyl bromide, at least on some occasions, for disinfestation and pest control

NURSERY PLANTS (cont.)

Rose	*Rosa* spp.
Snapweed	*Impatiens* spp.
Spleenwort	*Asplenium* spp.
Spurge	*Euphorbia* spp.
Stevia	*Stevia* spp.
Syngonium	*Syngonium* spp.
Tillandsia	*Tillandsia* spp.
Virburnum	*Virburnum* spp.
Vriesea	*Vriesea* spp.
Wormwood	*Artemisia* spp.
Yellow Poplar	*Liriodendron* spp.
Yucca	*Yucca* spp.

Annex 4.3.4

Table 4.3.2 Examples of Fumigation of IMPORTS as a Condition of Entry.

Country importing the commodity	Commodity	Target pest(s)	Quantity imported	Methyl bromide used
Canada	Pears	Lepidoptera	100 t	15 kg
	Mixed vegetables	Diptera and Coleoptera	2.5 t	1 kg
	Durian	Lepidoptera	4 t	0.3 kg
	Apricots and peaches	Lepidoptera	3.4 t	1.8 kg
	Other fresh fruit	Homoptera	2 t	1.2 kg
	Ya pears	Homoptera	?	1.8 kg
Chile	None reported			
Costa Rica	No data are collected on the use of methyl bromide			
Denmark	No fumigation of perishable commodities			
Egypt	Apple	Hemiptera Homoptera	1354 t	270.6 t
	Coconut	Coleoptera Hemiptera Diptera	759 t	74 kg
	Pear	Homoptera	35 t	8 kg
Germany	Two out of 16 states reported no fumigation of perishable commodities			
Hungary	No fumigation of perishable commodities			

Annex 4.3.4 (cont.)

Table 4.3.2 (cont.) Examples of Fumigation of IMPORTS as a Condition of Entry.

Country importing the commodity	Commodity	Target pest(s)	Quantity imported	Methyl bromide used
Japan	Fresh fruit	Acarina Lepidoptera Coleoptera Hemiptera	1582181 t	42.3 t
	Fresh vegetables	Acarina, Lepidoptera Coleoptera Hemiptera	269996 t	96.5 t
	Cutflowers and ornamentals	Acarina, Lepidoptera Coleoptera Hemiptera	329,467,000 pieces	11.6 t
	Fresh bulbs and tubers	Acarina, Lepidoptera, Coleoptera Hemiptera	277,559,000 pieces	163 kg
	Nursery plants	Acarina, Lepidoptera Coleoptera Hemiptera	71,273,000 pieces	2.1 t
Kenya	Stem cuttings, budwood, rooted plants, bulbs, cut flowers and miscellaneous fruit	Miscellaneous injurious pests and diseases	Not reported	3.7 t
Malaysia	Willow	Insects	Not available	< 15 t
Morocco	None reported			
Norway	No fumigation of perishable commodities			
Poland	No postharvest uses			
Singapore	None reported			
South Africa	None reported			

Annex 4.3.4 (cont.)

Table 4.3.2 (cont.) Examples of Fumigation of IMPORTS as a Condition of Entry.

Country importing the commodity	Commodity	Target pest(s)	Quantity imported	Methyl bromide used
South Korea	Pineapple	Homoptera	4848 t	85 t
	Grapefruit	Homoptera	5118 t	3 t
	Chicory	Homoptera	1.3 t	0.3 t
	Roses	Lepidoptera	2.1 t	1.2 t
	Orchids	Lepidoptera	182 t	1.8 t
	Ornamental fir	Coleoptera	3.2 t	0.7 t
	Nursery stock	Homoptera	300309 pieces	0.3 t
	Rhododendron	Nematode	2126 pieces	0.2 t
	Lily bulb	Nematode	230,000 pieces	1 t
	Fig tree	Nematode	152,999 pieces	0.1 t
Spain	Garlic	Lepidoptera	969 t	Not reported
	Coconut	Mites	1.2 t	Not reported
	Quince	Diptera	2.1 t	Not reported
Sweden	No fumigation of perishable commodities			
Switzerland	None reported			
Thailand	None reported			
United States	Fruit (16 types) & vegetables (13 types)	Various	6,100 t	109 t

Annex 4.3.5

Table 4.3.3 Examples of Fumigation of EXPORTS as a Condition of Entry.

Country exporting the commodity	Commodity	Main target pest(s)	Exported to...	Quantity exported	Methyl bromide used
Canada	Nursery stock (*Malus* spp.)	Homoptera Lepidoptera	USA and France	2900 pieces	2.7 kg
Chile				Million cases	
	Grapes	Acarina	USA	10,800	Not reported
	Plums	Various	USA	310	Not reported
	Peaches	Various	USA	217	41.6 kg
	Nectarines	Various	USA	183	Not reported
	Apricots	Various	USA	5	Not reported
	Tomatoes	Diptera and Lepidoptera	Argentina	168	680 kg
Costa Rica	No data are collected on the use of methyl bromide				
Denmark	No fumigation of perishable commodities				
Egypt	None reported				
Japan	Unshu oranges	Mealybug	USA	692 t	246 kg
	Bonsai trees, *Cornus* spp, *Cotoneaster* spp, *Rosa* spp.	Scale insects	UK	958 pieces altogether	2.5 kg
Finland	No fumigation of perishable commodities				

Annex 4.3.5 (cont.)

Table 4.3.3 (cont.) Examples of Fumigation of EXPORTS as a Condition of Entry.

Country exporting the commodity	Commodity	Main target pest(s)	Exported to...	Quantity exported	Methyl bromide used
Germany	Two out of 16 states reported no fumigation of perishable commodities				
Hungary	No fumigation of perishable commodities				
Iceland	No fumigation of perishable commodities				
Malaysia	Orchids	Thrips, mites	Japan	1,000,000 pieces	?
	Roses	Thrips, mites	Japan	20,000 pieces	?
Morocco	Potatoes	*Photorimea opercullela*	France and other European countries	24.7 t	12 kg
Norway	No fumigation of perishable commodities				
Poland	No postharvest uses				
Singapore	Orchids	Lepidoptera	Japan, USA	30,000,000 pieces	?
South Africa	Pineapple	Acarina	Europe, Japan	5080 t	4 t
	Carnation	Acarina	Europe, Japan	2 t	0.1 t
	Chrysanthemum	Acarina and nematodes	Europe, Japan, USA	10 t	0.75 t

Annex 4.3.5 (cont.)

Table 4.3.3 (cont.) Examples of Fumigation of EXPORTS as a Condition of Entry.

Country exporting the commodity	Commodity	Main target pest(s)	Exported to...	Quantity exported	Methyl bromide used
South Korea	Chestnut	Coleoptera	Japan, USA, Canada	342 t	17 t
	Cabbage	Homoptera	Japan	190 t	15.4 t
	Chinese cabbage	Homoptera	Japan and China	135 t	4 t
Spain	None reported				
Sweden	No fumigation of perishable commodities				
Switzerland	None reported				
Thailand	Orchids	Thrips	Japan, USA, Australia	118 million pieces	5.5 t
	Asparagus	Thrips and Lepidoptera	Japan	1864 t	1.7t
United States	Cherries	Lepidoptera	Japan, Korea	16,400 t	7.3 t
	Peaches	Lepidoptera	Chile, Israel, Morocco, Tunisia	?	?
	Nectarines	Lepidoptera	Chile, Israel	?	?
	Strawberries	Thrips	?	?	?

[1] Million cases

Annex 4.3.6

Table 4.3.4 Examples of Fumigation for SHIPMENT WITHIN THE SAME COUNTRY.

Country	Commodity	Target pest(s)	Shipped from...to...	Quantity shipped	Methyl bromide used
Canada	Nursery stock (*Malus* spp.)	*Grapholitha molesta*	Ontario to British Columbia	16,000 pieces	14 kg
	Fruit trees - rootstocks	*Grapholitha molesta*	Ontario to British Columbia	50,000 pieces	15 kg
Chile	Tomatoes	*Ceratitis capitata* fruit fly (Diptera)	Arica region in north of Chile to Central Region	30,000 t	2.5 t
Japan[a]	Kidney bean	Melon fly	Yaeyama Islands to other regions	38 t	114 kg

[a] From 1993, melon fly (*Bactrocera cucurbitae*) has been completely eradicated from the south west regions of Japan including the Yaeyama Islands removing the need to fumigate commodities with methyl bromide prior to shipment to other regions in Japan.

4.4 Alternatives for treatment of structures and transportation

Executive Summary

Structural fumigation is a pest management technique that uses a fumigant on either an entire structure or a significant portion of a structure. The structures may contain raw agricultural commodities, raw products in process or finished food products awaiting delivery to distribution points. Fumigation is utilised whenever the infestation is so widespread that localised treatments may result in reinfestation or when the infestation is within the walls or other inaccessible areas.

Methyl bromide is currently used as a structural fumigant in three types of facilities: food production and storage (mills, food processing, distribution warehouses), nonfood facilities (dwellings, museums), and transport vehicles (trucks, ships, aircraft, railcars). Target pests include stored product pests (mites, beetles, moths), cockroaches, silverfish, psocids, flies, spiders; wood destroying insects (termites, beetles); and rodents.

Pest management in these facilities is best achieved through the use of integrated pest management (IPM) procedures. A reduction in the use of fumigation in IPM programs can be accomplished, depending on the degree to which other procedures are implemented. Even the best IPM programs may occasionally require a full site treatment, currently fumigation with methyl bromide.

With regard to treatment of structures for pests other than wood destroying insects, in most situations there is currently no alternative treatment to methyl bromide for eradication. In some cases the most efficacious fumigant is phosphine but its corrosive properties, resistance and time required for fumigation limit its use in some situations. Hydrogen cyanide is another efficacious fumigant, however it is only used on a limited basis in a few countries due to its acute toxicity. Strategies which incorporate phosphine, carbon dioxide and heat are being tested as alternatives.

Most alternative strategies to methyl bromide fumigation incorporate the use of nonfumigant pesticides and nonchemical procedures. Heat treatment is probably the most effective full site nonchemical technique for pest elimination in structures that, along with the equipment, can withstand the increased temperatures.

Although methyl bromide is often used in some countries to treat wood destroying insects, other methods have been available for many years, including sulphuryl fluoride, nonfumigant pesticides and nonchemical methods. In non-food situations sulphuryl fluoride is a substitute full site fumigant for these pests and its use is increasing. However, the control of some insect life stages requires a significantly higher fumigant concentration (10x). Phosphine with carbon dioxide and/or heat has been used to control these pests in some situations.

Of the nonchemical procedures heat is the one that most closely approximates fumigation in effect against wood destroying insects. However, it poses the risks previously mentioned for other structures and pests. Most other chemical and nonchemical treatments, such as liquid nitrogen, electrocution, and microwave are spot treatments that rely heavily on the technician's ability to locate the site(s) of infestation.

Ships, aircraft and other transport vehicles pose particularly difficult pest management problems because they often contain sensitive equipment, innumerable harborages and it is often not economically feasible to keep them out of operation for more extended periods of time. Furthermore, methyl bromide is the only fumigant allowed for many quarantine treatments on ships in many countries. Presently there are no acceptable alternatives to methyl bromide for rodent and insect elimination aboard aircraft.

There are opportunities to reduce methyl bromide emissions through better containment and monitoring, which has the additional benefit decreasing treatment time. The use of methyl bromide in combination with carbon dioxide can reduce use by 50% or more. Certain structures, such as aircraft, lend themselves to developing strategies for recapture, recycling and/or destruction of methyl bromide.

Research is needed in many areas before alternative strategies can be adopted. In particular, more data are needed on critical temperatures for heat treatment, biological controls, modified atmospheres, combination treatments, and potential fumigants.

As these new technologies are developed there is a continuing need for technology transfer, and this will be one of the major problems confronting developing countries. Programs for the transfer of knowledge and training must be developed to bring about a successful transition to reductions of methyl bromide use and emissions and/or to replace methyl bromide with alternatives and substitutes for structural pest control. Particularly crucial is training in pest identification, biology and habits, monitoring and use of new technologies. The success of this training is dependent on economic, social and cultural conditions in developing countries.

Various constraints exist which affect the adoption of substitutes and alternatives. At the present time there are situations where there are no feasible alternatives for food processing structures or in conveyances containing sensitive metals, particularly aircraft, when pest eradication is the goal. A critical element in determining the use and effectiveness of alternatives is the establishment of economic thresholds for the various pests. Differing regulatory requirements and use constraints throughout the world will determine the availability of alternative pesticide products and fumigants.

The economic constraints of substitute and alternative strategies must also be considered. For example, the use of sulphuryl fluoride is not allowed where food is exposed; and phosphine has some limitations on its use. High demurrage rates for ships, nonoperational time for aircraft and extended closure time for mills can significantly increase pest management costs and the cost of goods sold.

4.4.1 Introduction

Structural pest control is used to prevent or control pests in either an entire structure or a portion of a structure. The structures may contain raw agricultural commodities, raw products in process or finished food products awaiting delivery to distribution points, non-agricultural materials, or may be empty. In this context, pests include insects and other arthropods, as well as rodents and other vertebrate pests.

The types of structural facilities which are treated are conveniently grouped into three categories:

- Food production and storage facilities - buildings primarily used for the production or storage of food, e.g., mills, food processing plant, distribution warehouse, and others.
- Nonfood facilities - buildings not primarily used for the production or storage of food, e.g., residences and museums.
- Transport vehicles - conveyances that are empty but may be infested and need to be treated, and can be considered mobile storage areas. If loaded with foods, the treatment is normally classified as a commodity treatment since the commodity would be the primary source of an infestation.

The necessity to minimise pest infestations and attempt to eradicate pests in food is well documented. Infestations can migrate from infested commodities into the structure of the building. This can result in new consignments becoming infested as insects move from the structure. Therefore, structural treatments can involve empty buildings or those containing goods.

Stored products pests consume and contaminate commodities and affect their chemical, water balance, and heat characteristics. Presence of arthropods or their excretory or secretory products in food or dust may have health implications for consumers and workers, including induction of allergic responses (Wirtz, 1991).

This underscores the need for maintaining stored product pest infestations at the lowest level practical. The choice of treatment depends on the goal. Pest elimination, at least occasionally may require full site treatment, which today usually includes use of a fumigant, while pest control only may be achieved in many cases by more sustainable treatments.

The presence of food and other materials in these facilities dictates the type of treatment which may be utilised. Some fumigants, for instance, have no food tolerances set or may adversely react with nonfood materials in the structure.

Structural fumigation is a pest management technique that provides broad spectrum control and the ability of the fumigant gas to penetrate to pests that are not on the surface and cannot be readily contacted by other types of pesticide applications. The ability to penetrate through packaging materials, walls, and other areas to hidden infestations is particularly valuable in structural fumigation.

Any integrated pest management (IPM) program for structures must begin with identification of existing and potential pests, the cause of their presence, their vulnerabilities, and consideration of all practical chemical and nonchemical controls with adequate consideration to product and worker safety and the environment. Programs will normally involve several techniques. Even the best IPM program of combined techniques may be occasionally inadequate, and a full site treatment, generally fumigation, will then be needed.

Methyl bromide is registered for a wide variety of treatments including where food is present. It is effective against all life stages of insects and vertebrates. It penetrates well and permits short fumigation times, often no more than one day. There is little known resistance and its efficacy is well researched and understood. Because it is acutely toxic, it should be applied by skilled applicators and requires a minimum of three days aeration in some applications, notably dwellings in USA.

Currently, methyl bromide for structural applications accounts for approximately 3.0% of worldwide non-feedstock methyl bromide use, calculated on methyl bromide sales data (Table 2.1). The survey of uses of methyl bromide carried out by the MBTOC subcommittee considering methyl bromide use and alternatives for structural fumigation resulted in a slightly larger proportion and larger estimate of total tonnage used in this sector (3,736 t compared with 1,964 t for 1992). Possible causes of this variation have already been discussed (Section 2.4). Breakdown of use by country and application is shown in Table 4.4.1.

Table 4.4.1 Methyl bromide usage for structural pest control. Global estimate for 1992

Country	Total MeBr usage (t)	% use in structures	% mills	% ships	% domestic	% bubble[a]	% heritage	% containers	% silos	% aircraft
Africa (unless specified)	1838	5								
Australia	848	20				1		16	3	
Bahamas	1.5	100	10		80			10		
Barbados	.25	100			70		10	20		
Belgium	300	10				2		8		
Canada	270	90						90		
Denmark	33.3	14	12				2			
Eire	60	30	16				6	6	11	1
Fiji	9.5	25			25					
Finland	6.5	100	98				2			
France	1604	11	10					1		
Germany	<100	70	30			5	30	5		
Greece	900	10				10				
Hong Kong	21	50						50		
India	135	60	20	20			20			
Indonesia	153	0								
Israel	3500	1								
Italy	7500	2				2				
Japan	9430	0.03					0.03			
Kenya	257	30								
Malaysia	70	0								
Netherlands	39	68	30	10	0	1	5	12	9	1
New Zealand	143.5	20						20		
Norway	11	97	85	1			11			
Singapore	42.6	11				1	10			
South Africa	716	20	5	5	5				5	
South America	1621	5	5							
Spain	3605	11	5	5		1				
Sweden	18	99	76				23			
Trinidad	1.6	100			74	1				25
United Kingdom	550	10	3	2		2	1	2		0.1
USA	28100	6	2		2					
TOTAL	61864									

Sources: United Kingdom Fumigation Company; Bromine Compounds Ltd, (Dr M. Spiegelstein), Israel; Dr J.A. van Haasteren, Ministry of Housing, Netherlands; Hallas et al. (1993); MAFF, Plant Protection Division, Japan.

[a] Bubble, a sealed plastic covered system

4.4.2 Existing uses of methyl bromide in structural fumigation

Many conditions and pests exist which require structural pest control; only some of these are treated primarily by methyl bromide fumigation. There are three main applications: 1) control of direct structural damage by drywood termites and wood-boring beetles to domestic, commercial and historic buildings, 2) control of pests, for example moths, beetles, cockroaches, mites, and rodents, in food processing or storage facilities and non-food facilities, and 3) control of pests, for example moths, beetles, cockroaches and rodents, in transport vehicles, including ships, trucks, aircraft and freight containers.

The following list contains many of the current uses of methyl bromide for structural fumigation, and is followed by a discussion of substitutes and alternatives that have either been used or ones that might be utilised. Additionally, research is needed to verify the viability, limitations and conditions of some alternatives and to develop others that are still experimental or in the planning stage.

4.4.2.1 Pests Other Than Wood Destroying Insects. Methyl bromide is currently used in many countries for this category of structural fumigation.

Description	**Examples of Pests**
Food Production and Storage Facilities	
Food processing plants Flour and feed mills Bulk commodity storage (e.g. silos) Warehouse Bakeries Ham smoke houses Cheese plants Refrigerated storage Restaurants	Stored product insects, rodents, cockroaches, psocids, mites, silverfish, beetles
Nonfood Facilities	
Seed warehouses	Rodents, stored product insects
Museums	Dermestid beetles, clothes moths, cigarette beetles, drugstore beetles
Poultry houses	Lesser meal worm, mites, rodents
Mushroom houses	Mushroom flies, mites
Condemned housing or public health compliance	Rodents, cockroaches, venomous spiders

4.4.2.2 **Wood Destroying Insects**. Methyl bromide is used for this category of structural fumigation only in the USA and in a small number of other countries.

Dwellings including apartments, condominiums, trailer homes, historical buildings	Drywood termites, furniture beetles, powder post beetles, long horned beetles
Structural elements before building or in place, e.g., beams	Powder post beetles, long horned beetles
Museums	Wood boring beetles
Antique vehicles	Powder post beetles

4.4.2.3 Transport Vehicles

Trucks, truck trailers, vans (empty)	Beetles and moths
Ships, shipholds, galley & quarters (empty)	Insects & rodents
Railcars (freight or commodity)	Insects & rodents
Buses	Insects
Aircraft	Cockroaches & other insects, rodents

Methyl bromide can be used on an entire structure or a portion of a structure. Treatment duration is dependent upon the time taken to achieve a set *ct*-product. Ideally sufficient gas to kill the pests is released into the space and then maintained at the toxic level for a defined period of time. Methyl bromide is a highly volatile gas that requires containment for at least several hours so the fumigant can reach pests. The current practice in many countries is to fumigate with methyl bromide during a three day weekend when operations are typically suspended.

When a structural fumigation with methyl bromide is completed, the gas is currently ventilated into the atmosphere. Structural components and materials can absorb the fumigant and release it slowly into the interior of the structure for a period between a few hours and several days after aeration has been actively terminated; the length of time needed to safely aerate a structure depends on the materials which compose and are contained in the structure, and the method of aeration employed (CA-EPA/DPR. Fumigation Study Data, Methyl Bromide Treated Houses. March 1992. CA. USA). Low lying areas may be particularly difficult to clear of fumigant.

There is no data available to indicate that methyl bromide breaks down to nonvolatile components during structural fumigation. It is assumed that most (>95%, TEAP Report, 1994) methyl bromide used for structural pest control ultimately is emitted directly into the atmosphere (U.S.A. Department of Health and Human Services, ASTDR. Toxicological Profile for Bromomethane. September 1992. WA, DC. U.S.A; Hazardous Substances Data Bank. Nat. Toxicology Information Programme. 1989. U.S.A).

4.4.3 Substitutes and alternatives to methyl bromide

4.4.3.1 Substitutes and alternatives for pests other than wood destroying insects

Integrated Pest Management (IPM) programs may be used for structural pest control in mills and food processing sites (the same principles apply to other structures where non wood destroying insects are to be controlled). The objective of any IPM program in this situation should be to achieve the desired level of pest control by:

- Using no or minimum amounts of pesticides;
- Minimising disruption to the mill or plant;
- Maximising cost effective techniques; and
- Minimising health and environmental effects.

In specific situations some of the parameters listed above can be contradictory and a choice must be considered. Also a choice must be made with regard to the desired level of pest control and the degree of treatment (implementation of the IPM program). If the desired level of pest control is freedom from insects in the product leaving the mill or the processing plant, then the following should be included in the pest management program:

- **Sound construction and maintenance practices**. These play a major role in reducing pest harborages and denying pests access to structures and enhance other alternative treatments, e.g., by improving containment, using materials not heat labile, and reducing the need for residual and other pesticide applications. New construction should include pest prevention as a priority. Retrofitting existing facilities can be considered. Costs of this action will vary widely on a case-by-case basis.

- **Sanitation**. Sanitation is the preliminary step in most IPM programs for the management of structural pests, regardless of any other procedures used. Sanitation reduces pest food and harborages and can enhance other alternative strategies by cleaning up waste and debris that pests can eat, and where they can breed and live.

- **Detection and monitoring**. Suitable detection devices should be installed, maintained and regularly checked to provide early evidence of insect, rodent and other pest activity. This should include monitoring of all incoming materials (which should preferably be treated and guaranteed free of infestation prior to delivery) and monitoring of outgoing product. Regular and frequent (preferably weekly) inspections by trained personnel should be conducted throughout the premises and findings recorded. Records should include pest activity and aspects of sanitation, construction, and maintenance, that need alteration to prevent pests from becoming established. This sometimes requires close liaison between pest control professionals and site staff.

- **Preventive treatments**. A program of preventive treatments should be instigated that are designed to prevent pest infestation from developing in relevant areas. These are likely to be within the walls of the structure (where, for example, inert dusts may be used), and within the milling or processing equipment (where for example it may be necessary to strip down and clean machinery at regular intervals).

- **Localised site specific treatments**. Immediately after detecting any infestation, a site specific treatment should be used. A program can be agreed and specified in advance of pest infestation, so implementation can be achieved quickly. However standard treatments will often require some modification to meet the requirements of any particular situation.

- **Full site treatments**. Full site treatments are used to eradicate an infestation that cannot otherwise be adequately controlled. Due to the particular difficulties in achieving pest control in flour mills and similar food processing sites, it has usually proved necessary for a complete site treatment to be carried out at various intervals.

Some IPM programs in countries with relatively cold climates have avoided the necessity for complete site treatments for several years. When an infestation becomes established within the walls, floors, machinery and other inaccessible areas, the site will need treating in a way which will ensure penetration and eradication or to stop production in that building and move to another site. In full site treatments, eradication of pests is the objective, rather than control by reducing the population to a more manageable level. This is because if the population is reduced but not eradicated, it will more quickly revert to a population level that again requires full site treatment. Secondly, partial control rather than eradication can often encourage resistance to develop (this may apply to both chemical and nonchemical methods). If this happens it will make future full site treatments and IPM programs less effective. IPM because of its multi-technique approach can delay the onset of resistance.

Alternative full site treatment options to methyl bromide include:

Carbon dioxide
Cold
Controlled atmospheres
Heat
Hydrogen cyanide
Phosphine

or combinations of these options.

The choice is determined by regulatory approvals, the prevailing weather conditions, the type and condition of the building, contents, the time available, the relative costs, health and environmental risks and the species of pest present.

There is no one method or material to replace methyl bromide for structural fumigation for all situations in which it is currently used (Watson *et al.*, 1992). IPM approaches employing site specific detection, physical remedies, other pesticides and monitoring and appropriate training of pest control workers will provide a framework for alternatives to some methyl bromide applications.

It is theoretically possible that if new structures are constructed to minimise pest harbourage, and maximise the effect of sanitation then it will be possible to reduce further the necessity for complete site treatments. In cold climates it may be possible to avoid the necessity for complete site treatments altogether. In suitable buildings heat treatment can be effectively used in many situations to achieve pest eradication.

Meanwhile, most existing mills and similar processing sites using the most sophisticated IPM programs will, based on present evidence, continue to require a complete site treatment within the IPM program from time to time. Future development of these programs should therefore include specific attention to integrating strategies (for example building design, construction, and alterations) that will allow alternatives to methyl bromide to be used for complete site treatments.

Although methyl bromide is often used to treat for pests other than wood destroying insects within structures, other methods have been used for many years in specific cases.

These alternatives can be grouped into three categories:

- Fumigants
- Nonfumigant pesticides
- Nonchemical methods

4.4.3.1.1 Fumigants

Phosphine is often used in grain fumigation and can be used in some structural situations. It provides good penetration and its efficacy against some pests is well researched and understood.

It can cause corrosion problems on copper, or gold and silver alloys. Damage to electrical and other equipment occurs more frequently in hot humid weather. The extent of this problem needs to be investigated further under varying conditions. The use of phosphine is not recommended below 10°C (50°F) because it provides limited control at low temperatures. It is not approved for dwellings and other structural fumigation uses in the U.S.A. Depending on temperature and humidity, fumigations with phosphine may take five or more days, in contrast with one day for methyl bromide. In dealing with leaky structures, as with methyl bromide, it has been recommended that the phosphine dosage rate should be increased to compensate for leakage (Mills *et al.*, 1990). Additional phosphine may also be added during the treatment.

Phosphine kills most stored product pests but does not provide adequate control of several mite species that are important stored grain pests. Resistance of some insect species to phosphine has been documented in various parts of the world. There is a high degree of intra-specific variation in tolerance with eggs and pupae being much more tolerant than larvae and adults (Mills *et al.*, 1990). Time of exposure was more critical than dosage for both susceptible and resistant strains. Control of resistant populations requires high dosage and long periods of exposure (Price and Mills, 1988). Alternating phosphine use with other fumigants is one potential way of slowing development of resistance.

There is a danger of fire, or even explosion, when phosphine formulations are misused or resulting residues improperly handled. Aluminium phosphide formulations, the most common form of phosphine-generating product, may contain 3% or more of undecomposed phosphide, presenting a disposal problem and further potential hazard.

Sulphuryl fluoride can be a substitute for methyl bromide in countries where it is available and registered. At the present time, sulphuryl fluoride is only available in the United States, Germany, Japan, Sweden and the Caribbean. It is not registered for use where food and grain commodities are present and is not likely to be because food residue tolerances have not been established. The manufacturer does not intend to pursue this registration (DowElanco, communication to MBTOC).

It is very effective against all life stages of wood destroying insects. The efficacy of this product is well researched and understood. It provides good penetration, requires a short fumigation period of approximately 24 hours, and has a 6 - 8 hour aeration period.

To kill the egg stage of many insects requires up to a 10x increase in dosage when compared to the normal rate for control of adults. The economics of the higher dosage must be a considered in evaluating this treatment. If good sealing techniques, which enhance fumigant containment are achieved, lower dosages may be rendered more efficacious by enabling the exposure period to be extended. The economics of plant down time must be considered when determining the exposure period. It must be applied by skilled operators.

Hydrogen cyanide (HCN) has been used as a fumigant for almost a century and still has some uses in a few countries. It is the only fumigant gas that is lighter than air. This product acts very rapidly in suitable locations, particularly against rodents. It is easy to apply and has very little residue if used correctly.

HCN is no longer used in most countries for a variety of reasons including the fact that it is extremely toxic to humans and skin absorption alone can cause death at the concentrations normally used. During normal fumigations inadequate distribution can occur and localised concentrations can be explosive. It is very water soluble. This property can interfere with penetration and cause exposed water to become toxic. Its reaction with some foods produces toxic compounds. There are severe restrictions imposed on its transport.

4.4.3.1.2. Controlled Atmospheres

Considerable research has been conducted on disinfestation of stored commodities with controlled atmospheres (see Sections 4.2.3.1.10 and 4.2.4.3.2) and data obtained in those studies may be pertinent to structures.

Controlled atmospheres can be characterised as ones which either deficient in oxygen or rich in carbon dioxide. Carbon dioxide acts as a toxic gas on insects, whereas atmospheres made with nitrogen act solely through lack of oxygen to support life. These techniques offer the advantage that no toxic residues remain on food contents in the structure.

Presently, there are few flour mills or other food manufacturing plants that are well sealed enough to hold the required concentrations for the required amount of time, usually more than 10 days, without excessive use of gas. Structural modifications for older food production facilities or new construction could be expensive. This technology can be incorporated into new construction. Accidental tearing of the seal during long exposure periods, which can cause failures, is more likely than with shorter duration fumigations. Heat exchangers and other specialised equipment are often needed for treatment of large structures for distribution and circulation of the gas. There is active research in generation of gases for modified atmospheres for insect control. Machines capable of generating such gases on site have already been trialled for treatment of grain pests in large silos (Cassells *et al.*, 1994).

4.4.3.1.3 Combinations

Fumigant + carbon dioxide
Fumigant + heat
Fumigant + carbon dioxide + heat
Fumigant + fumigant

The most significant advantage of using combinations is the reduced amount of fumigant required for effective treatment. This also can reduce costs. These procedures have the potential to reduce risks of human and environmental exposure, and aeration time.

Phosphine (0.09 - 0.14 g m^{-3}) combined with heat at 32 - 37°C and CO_2 (4 - 6%) has proven to provide good penetration and a rapid treatment time, similar to that for methyl bromide (Mueller, 1994). Additional data is needed on efficacy and the advantages and limitations of these techniques, particularly damage to sensitive metals in equipment.

4.4.3.1.4 Nonfumigant Pesticides

Space Sprays (fogging, misting) usually involve dispersal of small particles below 50 microns in size dispersed in the air at a rate of 0.5 to 1.0 g m^{-3}. The small particles stay suspended in the air for a period of time and contact and kill exposed insects. It can supplement other control methods as part of an IPM program, but is seldom a complete control itself, since space sprays are not assumed to have penetrating ability and therefore cannot move between stacked bags or penetrate the bags where eggs and larvae are normally developing. Space sprays such as pyrethrins, pyrethroids or dichlorvos have limited residual properties, limiting their ability to kill the insects not directly contacted (e.g., insects hidden in walls, floor drains, and other protected areas such as production machinery from which insect infestations can spread). These space sprays can also contribute to IPM programs.

Space sprays formulated with oil-based solvents should be applied carefully in order to avoid explosions from excessive concentrations. Staining can occur. Foods must be removed and food contact surfaces must be covered or cleaned after application. Dichlorvos is the most effective space spray because its volatility is 320 times greater than most space sprays. In the U.S.A., the food additive tolerance for dichlorvos is under review, thus in the future it may no longer be used where processed or packaged food will be contacted. This effectively limits its use to nonfood areas and its toxicity may lead to further restriction and unavailability.

Surface Application of Liquid Residual Pesticides is a part of most pest management programs in food production plants. The target pests most often are stored grain insects, mites, psocids and cockroaches. When directed pesticide applications are made into the insect harbourage, infestations outside the product or raw commodity can be reduced. Residual applications are relatively easy to apply when compared to fumigation and can be effective for an extended period of time. These applications are usually combined with other techniques. Organophosphates, carbamates and pyrethroids are classes of pesticides typically used.

Since there is virtually no penetration beyond the point of application and it is difficult to apply insecticides to all harbourage sites and other areas of insect activity, pest elimination is often unattainable. In an IPM program both type of compound and application method can be adjusted to the specific local needs. Precise hand application is time consuming and expensive. Longevity of residual materials may be significantly influenced by surface composition, presence of other materials (such as dust, grease, food residues, etc.), temperature, humidity, etc. Some residual materials are repellent, causing insects to move to untreated surfaces.

Residual Dusts. These are usually applied in dry and relatively undisturbed areas, such as wall voids, under equipment, etc. Many of the active ingredients previously mentioned in this report are formulated into dusts. Two additional active ingredients not previously mentioned are boric acid and other borate formulations. Dusts have a long residual life when they remain dry, and even when applied at relatively low concentrations. They do not adhere well to surfaces and are easily moved from the site of application. In open areas they can be unsightly.

4.4.3.1.5 Nonchemical Treatments

Sanitation is the preliminary step in most IPM programs for the management of structural pests, regardless of any other procedures used. It reduces pest food and harborages within and without a structure by regular removal of waste and debris by vacuum cleaning, sweeping and washing, and can enhance other alternative strategies.

Construction and Maintenance play major roles in reducing pest harborages and denying pests access to structures. New construction should include pest preventative design as a priority. Retrofitting involves changes to the structure such as repairs and closures of pest entrances and niches, including caulking and applying new surfaces, and may be as extensive as replacing whole sections of structures. Retrofitting existing facilities is an economic consideration. Maintenance and construction practices can enhance other alternative treatments, e.g., by improving containment, allowing heat treatment, and reducing the need for residual pesticide application.

Inert Dusts, such as silica gel and diatomaceous earth, act as desiccants and can provide long residual control of crawling insects in wall voids and a few other locations. They are most effective against insects with a thin cuticle such as psocids, silverfish or insects that depend on an oily or waxy coating to preserve body moisture. Most inert dusts are rendered ineffective by high humidities, greater than about 80%. They adhere weakly to surfaces and are easily removed from the site of application. Silica gel and diatomaceous earths can be applied as a slurry. They can be unsightly and are usually used in areas such as wall voids that are not visible.

Diatomaceous earth formulations are relatively non-toxic, provided they do not contain crystalline silica.

Heating above 52°C (125°F) has been used to control insects in flour mills for almost 100 years. It is still used extensively by a number of major food processors as an important part of their pest control program. Food plants that can be successfully heat treated rarely require fumigation. It is also advantageous in that there are no residues. Although expansion of use of this technique is expected, there are some important limitations. For example, some structures cannot tolerate the stresses caused by extreme changes in temperature and differential expansion of structural components, e.g. of concrete and steel. Insects can sometimes migrate temporarily to outer walls or floor drains and successfully escape the effect of heat treatment. Some life stages may tolerate elevated temperatures for extended periods of time, a factor that requires further research. Heat dissipation is often slow, and may delay resumption of normal activities. Some equipment must be modified or removed to avoid damage. Some greases may liquefy and must be reapplied after heat treatment. Some products cannot withstand the required temperatures and may have to be removed and treated separately to prevent the reintroduction of pests. Some buildings are not constructed so that they can be uniformly heated to the required temperatures. Certain aspects of this technique are discussed in the attached case history (case history 4.4.1).

Trapping Devices can be used to monitor pest populations and as a technique for limited control (case history 4.4.2). Both the monitoring function and the function of limited control are valuable as part of an IPM program. These devices include glue-board traps, glue-board and electrocuting light traps and other devices such as pitfall traps. Trapping may be enhanced by the use of baits and/or pheromones. Mechanical traps for rodents can be effective; understanding feeding and nesting requirements of different kinds of rodents allows traps to be utilised most effectively. Traps can also deter the entrance of pests into a facility and they can be used for the early detection of pest populations.

Traps should be properly placed to avoid attracting pests into the structure or an internal area where they would not normally be found. In addition, insects living in closed structures such as machinery may be unable to reach traps.

Rodent traps include snap, glue and live trapping devices. They are particularly effective in reducing rodent populations within structures. They can be labour-intensive because they require frequent inspection and maintenance. Glue boards are considered inhumane in some countries. Rodent eradication by trapping may require an extended period of time in contrast to the rapid action of fumigation.

4.4.3.2 Substitutes and alternatives for wood destroying insects

Although methyl bromide is often used to treat wood destroying insects, such as powder post beetles, long-horned beetles, drywood termites and carpenter ants within structures, other methods have been available for many years.

These alternatives can be grouped into three categories:

- Fumigants
- Nonfumigant pesticides
- Nonchemical methods

Detection of wood destroying insects involves identifying and finding the specific location of pests so that control measures can be applied to the infested area when possible and practical. Monitoring pests is an on-going process of assessment of continuing pest presence where treatment procedures have been utilised. Several tools are used to supplement visual inspections to detect the presence of pests in wood, including specially trained dogs, optical devices, acoustic emission detectors, and methane detectors. The ability to detect the locations of the pest population is critical to some of the techniques described below, since several are effective only as spot treatments.

Methyl bromide fumigation is particularly used to eradicate drywood termites from structures. Current research indicates that termites are very heat and cold sensitive. When seasonal changes occur, drywood termite colonies move significantly within the structure. During warmer times, they move from exterior wall areas and attic spaces to other locations deeper into the structure where temperatures are cooler. Conversely when colder temperatures exist, the opposite movement occurs. This may make detection and spot treatment of an entire colony more difficult to achieve. Additional research indicates that when an entire colony is not eradicated it will produce new reproductives and survive. Subsequently, eggs will be produced and a colony can recover and potentially continue to damage the structure.

4.4.3.2.1 Fumigants

Sulphuryl fluoride is a substitute for methyl bromide in several countries where it is available and/or registered for use. In the USA (California) this substitution has led to virtually a 100% reduction in methyl bromide use in the fumigation of dwellings now. Usage fell from about 2300 t in 1990 to 430 t in 1992. The efficacy of this product is well researched and understood. It provides good penetration, requires a short fumigation period of approximately 24 hours and has a 6 - 8 hour aeration period. It is effective against all life stages of wood destroying insects. However, the egg stage of many insects requires up to a 10x increase in dosage when compared to the normal rate for adult control. The economics of the higher dosage are a consideration in evaluating this treatment. If good sealing techniques, which enhance fumigant containment are achieved, lower dosages may be made more efficacious by extending the exposure period. Sulphuryl fluoride is nonreactive and thus can be the preferred fumigant for libraries and museums.

At the present time, sulphuryl fluoride is only available in the United States, Germany, Japan, Sweden and some parts of the Caribbean. It must be applied by skilled operators.

Phosphine is often used in grain fumigation and can be used in some structural situations. There is limited efficacy data for wood destroying insects; this requires further research or documentation to determine the feasibility of using this product in dwellings. It was effective against wood-boring insects in Norwegian churches (case history 4.4.3).

The use of phosphine in dwellings may be limited due to its corrosive properties, particularly on copper or gold, and silver alloys under high humidity conditions. Phosphine may require an extended fumigation time, 72 hours or more, against some pests and at low temperatures (<20°C).

Hydrogen cyanide has been used as a fumigant for almost a century and still has some uses in a few countries. Historically it has been used for long-horned beetles and other wood destroying insects.

HCN is no longer used in most countries because it is extremely toxic to people. Skin absorption can cause death at concentrations currently used. During fumigations inadequate distribution can occur and localised concentrations can be explosive. It is very water soluble, hence moisture can interfere with penetration and cause exposed water to become toxic. Its reaction with some foods produces toxic compounds. There are severe restrictions imposed on transport of HCN in cylinders, but it can conveniently be produced on-site from solid sodium cyanide.

Combinations

Fumigant + carbon dioxide
Fumigant + heat
Fumigant + carbon dioxide + heat
Fumigant + fumigant

The most significant advantage of using combinations of techniques is the reduced amount of fumigant required while still achieving an effective treatment. These treatments have the potential to reduce exposure and aeration time. The efficacy of reduced sulphuryl fluoride concentrations and carbon dioxide has been demonstrated by Scheffran and Su (In press). This technology requires further study in operational settings. Further research is needed on the effect of the combination of phosphine, heat and carbon dioxide which has been used against stored product insects.

Chloropicrin has been used in combination with other fumigants (principally as a warning agent) to control wood destroying insects in dwellings. It is highly toxic to various insects but is difficult to remove from sorptive materials and considerably more toxic on a weight for weight basis to humans than methyl bromide.

4.4.3.2.2 Nonfumigant Pesticides

Surface application/injection of liquid residuals is used for spot application to accessible wood. The products used for this application include organophosphates (e.g., chlorpyrifos), pyrethroids (e.g., permethrin), and borates (e.g., sodium octaborate tetrahydrate).

These products are applied as sprays, fogs, brush-ons and/or injections for treating accessible components. The efficacy of organophosphates and the pyrethroids against wood destroying insects is well documented. The efficacy of borates for drywood termites is promising and is undergoing further study.

Dusts include active ingredients such as boric acid, pyrethroids, silica gel, diatomaceous earth, and sodium octaborate tetrahydrate. These products are applied as spot treatments or into cavities created by insects in the wood. Dusts are efficacious against some wood destroying pests, e.g., carpenter ants and termites, and have long lasting residual activity when dry. Application of dusts can be labour intensive and require boring into the wood in the structure. Further work is needed to determine the efficacy of these products for other wood destroying insects.

Wood Preservative Treatment is a method of preventing wood destroying insect problems by applying a pesticide or preservative to wood pre-construction.

Some materials used for wood impregnation have been discontinued because of environmental effects. Pentachlorophenol was broadly used at one time, but is only in use in a few countries now.

A wide range of preservatives are available for vacuum or pressure treating wood, for example borates and copper containing compounds. Preservative treated wood is useful in new construction and renovations to prevent infestations.

Sodium octaborate tetrahydrate has proven effective, when adequate penetration of the wood can be achieved, for some wood destroying pests for which methyl bromide is currently used. Tests are being undertaken to quantify the efficacy of borate with drywood termites, the pest historically responsible for most of methyl bromide use in dwellings.

The use of arsenic and chromic compounds for pressure impregnation has several effects on the environment and human health, regarded as unacceptable in some countries.

4.4.3.2.3 Nonchemical

Construction and Removal. New construction should be designed for pest exclusion and prevention as a priority so pests cannot gain access to a building and the structure does not provide inaccessible harbourage for pests. For example, in many situations constructing wooden structures in a manner which protects the wood from humidity, destroying the conditions necessary for pest development, in many situations can be substituted for the use of chemical wood preservatives and protect the wood against attacks.

Infested wood in dwellings can often be cut out and replaced. While this can be an effective spot treatment, it is labour intensive. Where permitted, infested wood should be replaced with pre-treated wood.

Heat. Heating to greater than 46°C is reported to eradicate drywood termites. Higher temperatures are likely to give more rapid mortality but the limiting factor with regard to treatment time is expected to be the rate at which lethal temperature are attained throughout the treated structure. Further study is needed to determine what specific structural components and contents are affected by heat, and how these may be protected, and the quantity of energy required to attain eradication in practice.

Cold can be used as a spot treatment by the injection of liquid nitrogen into confined spaces such as wall voids. This technique cannot be used in inaccessible areas. Insulation in walls can affect cold distribution causing warm spots in walls. Interior surfaces can be stained and warping of wooden structural components is possible.

Electrocution has been used as a spot treatment. Application of electricity with a high wattage/low amperage device to accessible structural components is said to be lethal to termites. Further research is needed before this technique is recommendable.

Microwave heating has been used as a spot treatment with very limited success. It destroys insects by heating the moisture in wood, but can damage wood by scorching it. Further research is needed before this technique is recommended and may be only applicable to accessible wood.

4.4.3.3 Ships, Aircraft and Other Transport Vehicles

These are included here on the basis that any treatment required is likely to require many of the same considerations as buildings.

4.4.3.3.1 Ships

Methyl bromide is currently used for ship fumigation for:

Quarantine treatment of holds and/or accommodation for rodent control.

Quarantine treatment of holds either empty or full of cargo for insect control.

Treatment of cargo after loading and prior to sailing, either with ventilation before sailing or during the voyage.

Methyl bromide is currently the only fumigant allowed for many quarantine treatments on ships in many countries.

The alternatives currently available are HCN for rodents in Singapore, phosphine for insects and rodents, rodenticides and traps. HCN could be used in empty vessels alone where there is no water in the bilges, rodenticides and traps could be used more widely if maintained carefully and consistently or where the infestation is low and time is not a constraint. HCN has some advantages in the control of rodents because it rapidly kills them and their ectoparasites, principally fleas. Availability of HCN may be limited by regulations on its transportation and handling.

Phosphine appears potentially to be suitable as an alternative to methyl bromide for treatment of empty ships and barges for rodent and insect control prior to loading commodity. Some developing countries currently use methyl bromide for this purpose. While phosphine is rapidly lethal to rodents, its slow action against insect pests, and consequent demurrage costs, may limit its usefulness. Where ships contain cargo, in-transit fumigation with phosphine or modified atmosphere treatments may be feasible (see Section 4.2.4.3.1).

4.4.3.3.2 Aircraft

Methyl bromide is currently used to fumigate aircraft for rodents and sometimes insects; however attempts are typically made to control insects through residual or aerosol insecticide applications. Methyl bromide provides a rapid and guaranteed kill which is essential in the context of the cost of grounding aircraft and the risks to the aircraft if the rodents are not killed.

There are at present no well researched and acceptable alternatives. Phosphine is not recommended because of the corrosion risk, but could presumably be used in extreme circumstances, though at risk of affecting the aircraft controls and other electrical systems. Controlled atmospheres have been shown to be promising for rodent control, but require research.

4.4.3.3.3 Other Vehicles (freight trucks, railcars, etc.)

These vehicles may require treatment to meet quarantine requirements when empty and prior to loading. In some countries methyl bromide treatment is currently mandatory. Phosphine could be an alternative treatment. Nitrogen-based controlled atmosphere treatments are being considered for quarantine rodent control between Barrow Island and mainland Australia for treatment of trucks and containers.

4.4.4 Containment/methods for reducing current methyl bromide use

4.4.4.1 Improved Containment

The objective of containment in the use of methyl bromide for the fumigation of structures is to enable reduced dosages to be effective, and to reduce emissions to the atmosphere. Containment alone would not normally be considered as a viable possibility to reduce emissions to the atmosphere without effective recovery technology. However, improved containment and monitoring may in fact be considered as a strategy for reducing emissions from structures while maintaining efficacy.

Containment and emission reduction strategies for structures involve: leakage control; extending the fumigation period, while ensuring adequate *ct*-products are achieved; and pressure testing. This aspect of fumigation can be enhanced by improved monitoring of fumigant concentrations and adjusting dosages where found to be excessive. Recovery and recycling are under development to further reduce emissions (see Section 3).

Reduced emissions can also be achieved as discussed earlier by using reduced methyl bromide dosages in combination with carbon dioxide and/or heat.

4.4.4.2 Methyl Bromide and Carbon Dioxide

The MAKR system is an alternative treatment which combines methyl bromide and carbon dioxide to reduce methyl bromide dosage from 24 - 36 g m^{-3} to 8 g m^{-3}. By adding 10% carbon dioxide, the amount of methyl bromide required is reduced by 50 - 66%. The carbon dioxide is heated, expanded, and introduced into a structure with methyl bromide. The effects of carbon dioxide are twofold: it provides more efficient dispersion of methyl bromide into all parts of the structure; and increases the respiration rate of insects, reducing the amount of methyl bromide needed to eradicate the infestation. Currently this structural treatment is only registered in the United States.

4.4.4.3 Volume Displacement Techniques

Gas impermeable balloons have been developed for the displacement of empty space within structures. These may be used to reduce the quantity of fumigant required to fill a space. One of the present disadvantages of this strategy is that there may be inadequate circulation of the gas.

4.4.5 Transfer of knowledge and training

Programs for the transfer of knowledge and training must be developed to bring about a successful transition to reductions of methyl bromide use and emissions and/or to replace methyl bromide with alternatives and substitutes for structural pest control.

The mechanisms for the transfer of knowledge for many substitutes and alternatives already are well established in developed nations where extensive information is readily available in existing texts and other resource materials. New ideas and technologies are disseminated through industry journals and conferences.

Particularly crucial to lessening or eliminating methyl bromide for structural pest control is training for pest identification, monitoring and utilisation of new technologies. Programs for training pest control managers and personnel in developing nations should be tailored to social and cultural conditions, pest species and structural situations, and to provide human health and environmental protection in each region.

4.4.6 Research Requirements

4.4.6.1 Emission reduction for methyl bromide

Monitoring fumigant levels. Data is needed on the percentage decomposition of the applied methyl bromide as used currently in structures, to improve estimates of emissions to atmosphere from current practice in structures. The losses from well sealed and pressure tested structures need to be determined. This data would be useful for calculation of lower dose longer exposure regimens that would produce effective ct-products while reducing quantity of MeBr applied, and consequent emissions.

Combinations. Further evaluation of application methods of combinations such as carbon dioxide MeBr mixtures, which with increased exposure time, may lower the methyl bromide dosage.

Leakage control. Research is needed to develop improved methods to detect and reduce leakage during fumigation, to permit use of lower MeBr dosages.

Containment, recovery and recycling. Studies on MeBr recapture have been initiated in German flour mills, and may provide methods of using methyl bromide, while minimising emissions (see Section 3.7.2). This, and similar techniques, should be tested for applicability to other types of structures.

4.4.6.2 Substitutes and Alternatives

Phosphine. Methods of using phosphine which reduce or eliminate damage to copper and noble metals require further investigation. Detailed research is needed on methods of using shorter treatment times while at the same time retaining and improving efficacy to ensure resistance problems are not increased.

Biological control. These techniques currently have limited application for controlling pests in structures. Research on pheromones, parasites, predators and microorganisms is needed to expand their role.

Carbonyl sulphide. This gas is currently being researched as a fumigant for stored grain and structures. Efficacy has been demonstrated in laboratory studies (Desmarchelier, 1994) but field trials have not been reported. Potential problems with residual odours caused by the hydrolysis of carbonyl sulphide to H_2S or by its reaction to form other sulphur compounds, toxicity, corrosion and flammability must be addressed. Registration has not yet been obtained.

Sulphuryl fluoride. Studies are needed to assess the feasibility of extending the use of this product to structures in which food is present.

Modified atmospheres. These techniques warrant further studies on efficacy and treatment strategies that would achieve the same purpose as fumigation, i.e., pest eradication. Research should investigate shorter treatment times, while maintaining and increasing efficacy, protecting health and the environment. Demonstration trials are needed to show applicability to aircraft for rodent eradication.

Temperature modifications. The use of heat shows considerable promise and is already in use in some mills and for domestic premises (Ebeling, 1994), but further research is needed to develop data on efficacious treatments, mitigation for effects of heat on construction, and the construction or modification designs of facilities to permit the effective use of this technique.

Combinations. Research is needed on treatments using combinations of fumigants, modified atmospheres, and physical changes, (e.g., heat) to shorten treatment times by utilising the potential synergistic effects of combinations with lower dosage rates, e.g., combined low dose treatments of phosphine, heat and carbon dioxide. Likewise combinations of approaches for prevention of pest infestations (e.g., construction of warehouses, careful storage of commodities) should receive site relevant research priority.

4.4.7. Uses without alternatives

At the present time there are situations where there are no feasible alternatives for food processing structures or conveyances containing phosphine-sensitive metals, particularly aircraft, when immediate insect pest eradication is the goal.

4.4.8 Feasible reduction in methyl bromide use

The subcommittee of MBTOC involved in considering methyl bromide use and alternatives in structures estimated that a 49% reduction in usage was feasible in structures by 1998 and 53% by 2003, subject to the constraints listed in Table 4.4.2.

4.4.9. Constraints

There are a number of alternatives as indicated above which do provide control of pests without methyl bromide. However, when the goal is pest eradication, some treatments require an extended period of treatment to achieve pest eradication which, in some situations, may incur increased costs.

One of the critical unknown elements in the use of alternatives is the economic thresholds for the various pests. For example, industry practice and consumer expectation within the developed countries have generally set the pest tolerance threshold in food at zero. To achieve and maintain this standard mandates pest eradication, which at present is usually assured through effective fumigation.

Regulatory requirements throughout the world will determine the availability of various alternatives. Pesticide residue tolerance levels in food, and toxicological concerns regarding worker and public health and environmental protection may limit the use of certain products. If space sprays and residual pesticides are relied on more heavily, residues on food are more likely to occur. Currently some of the products and technologies discussed as alternatives are not available or registered globally.

The economic impact of using substitutes and alternative strategies requires enumeration. It is established that for the foreseeable future, even when IPM programs are being used, some form of full site treatment (fumigation or equivalent) is likely to be necessary from time to time in food production and storage premises, ships, aircraft and some other situations.

4.4.10. Developing country issues

The future availability of methyl bromide has to be considered on a global basis with regard to the impact of effective alternatives on food production and storage. This is dependent on the cost, effective technology transfer and availability of substitutes and alternatives, as well as the technical expertise to introduce and utilise alternatives.

Table 4.4.2 Estimates for feasible reductions in structural uses of methyl bromide by 1998 and 2003*

Uses of MeBr	Total usage (t) (31 countries)*	% of total structural MeBr use	% feasible reduction by 1998	% feasible reduction by 2003	Feasibilities/considerations on % reduction estimates
Wood-Destroying Insects					
A. Dwelling (termites)	603	16%	100%	100%	1998: If sulphuryl fluoride is available where MeBr is currently used
B. Heritage (e.g. museums)	75	2%	100%	100%	1998: If sulphuryl fluoride is available where MeBr is currently used
C. Bubble (e.g. artefacts)	307	8%	10%	20%	1998: Consumer willingness to use controlled atmosphere in bubble is limiting factor because of long treatment time
SUBTOTAL	985	26%	81%	86%	
Food Storage/ Processing Structures					
A. Flour mills	1,148	31%	50%	50%	Country legislation would increase, switch over to alternatives currently available, e.g. heat, if structures are modified
B. Ships	258	7%	5%	15%	The reductions shown are based on opportunities for longer treatment during transit. A need for rapid treatment at port due to quarantine is limiting
C. Aircraft	1.4	0.04%	20%	20%	Carbon dioxide treatment possible but only when plane can be grounded for an extended treatment time
SUBTOTAL	1,407	38%	33%	37%	
Unspecified Structural Use	1,343	36%	57%**		
TOTAL	3,736	100%	49%	53%	

* Based on data in Table 4.4.1

** An unweighted average of the percentage reductions

4.4.11 References

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Case History 4.4.1: Heat Treatment of Flour Mill and Cleaning House

A flour mill and a cleaning house located on the Kansas State University campus. These facilities are connected to other structures on the campus by a common heat tunnel.

Flooding in the midwest USA in the spring of 1993 led to the development of a heating and dehumidification system that proved successful in the disinfection of two flour mills. This system did not require capital investment in plant heating capacity. This procedure was tested because the common connection between university facilities was a deterrent to traditional fumigation.

This test was designed to determine the efficacy of heat treatment against stored products pests in these facilities. The buildings were sealed and eleven 50-kilowatt heaters were placed throughout the facilities and heat ducts were used as necessary. Temperature was monitored with thermocouples and bioassays (48 units) were used to determine efficacy.

The amount of methyl bromide replaced using this method could not be estimated because the sizes of the facilities were not indicated, other than the mill had five floors and the cleaning house had four.

This procedure was documented as early as 1911 and is being tested and used with increased frequency, particularly in the United States. The use of this technology is not regulated by any governmental agency since it does not involve the use of a pesticide, and quality assurance is a matter of company policy and is rarely formalised by regulation.

Heat treatment is used as a pest management strategy by some of the larger mills and food processors in the United States, when pest eradication is not required. Companies that are anticipating restrictions on products traditionally used in these facilities, i.e., methyl bromide and dichlorvos, and as an alternative to fumigation and/or space treatments are adopting heat treatments as alternatives. There is no data to document the number of facilities and the amount of commodity protected with this treatment.

The procedure based on the report did not appear difficult to research. The most difficult problem appeared to be the installation of the heaters and the necessity of posting a fire guard because the sprinkler system had to be inactivated.

To avoid damage, heat sensitive materials, such as plastic pipes and equipment, must be removed prior to treatment. To effect treatment the building must be sealed virtually to the same degree necessary for standard fumigation.

This treatment has been used for food production and storage facilities, as well as nonfood facilities. However, it is not known to have been used for transport vehicles.

The overall assessment of insect control was that it provided very good results, however a few adults and larvae survived the treatment at the floor level, at the lower levels in the structure and around windows. It took 15 - 18 hours to reach the target ambient temperature range of 52-54°C and 20 hours to reach this temperature in commodity samples.

Source: Manuscript in press. Dr. John R. Pedersen, Department of Grain Science and Industry, Kansas State University, Manhattan, KS 66506.

Case History 4.4.2: Moth Control in Flour Mills Using Mass Trapping, Mating Disruption and Attracticide Method

In the Mediterranean region, this moth is a major pest of flour mills. Infestations can be so great in seasons of high population density that machinery can become clogged, preventing the flow of food through the mill.

The treatment of this problem has previously entailed the use of two MeBr fumigations and several other applications of insecticide per year.

Control of this pest with synthetic pheromones has been investigated in Italy since 1986. Successful control of *E. kuehniella* and refinement of the methods employed suggest that this alternative may be usefully employed in other situations, particularly in food processing, where a pheromone has been developed for a problem pest. Three pheromone alternatives have been investigated:

1. Mass trapping combined with limited use of insecticides and sanitation: Funnel traps baited with sex pheromone were placed every 260 - 280 m^3, inside the mill, outside the mill near loading machinery and other outdoor sites. Annual fumigations were reduced from two to one, and in addition, a few limited insecticide treatments were applied. These treatments must be accompanied by careful cleaning, particularly in corners and inside machinery. The continued presence of the traps in the mill resulted in a pest population reduction of 95 - 97%. The traps removed males, preventing an increase in the residual population. Population density in the second year of trapping was 26% of the first year, and by the third year was 16% of the first year.

2. Mating disruption: This involves permeation of the atmosphere with a synthetic pheromone. It employs laminar dispensers which are positioned on walls and machinery. In a study involving infestation of an old, traditional flour mill, levels were reduced from thousands of pests to only a few males by the third year of study. Drawbacks are the large amount of pheromones used and associated costs and possibility of pheromone residues in foodstuffs.

3. Attracticide method: Synthetic pheromone was released by laminar dispenser with one side of the dispenser treated with cypermethrin insecticide. Significantly higher numbers of males were attracted to dispensers with light brown cardboard figures with sub-triangular forms resembling the female of the species. Dispensers were placed 1.80 - 2.00 meters from the floor every 220 - 280 m^3. This method obtained results similar to those achieved by mass trapping. Benefits include lower amounts of pheromones used than in mass trapping and mating disruption methods. This technique allows the use of a broad spectrum of insecticides to be applied selectively (to the dispenser), thus reducing deaths of beneficial insects which may occur with broader applications of insecticides.

Source: Trematerra, P. 1994. Control of *Ephestia kuehniella* Zell. by sex pheromones in the flour mills. Anziege für Schädlingskunde, Pflanzenschutz und Umweltschutz 67: 74-77.

Case History 4.4.3: Fumigation of Three Stave Churches in Norway, August - September 1984

Three 900 year old wooden churches located in the Sognefjord area of Norway were fumigated. Some were decorated with original illuminated carvings and paintings. Some of these had been painted directly onto the wooden walls and had been damaged by the House Longhorn Beetle (*Hylotrupes bajulus*).

The infestation was probably present for many years and some control had been achieved in the past by spot treatments. During detailed surveys, serious infestations were found in the roof timbers and behind hidden panels. Wooden timbers could not be treated using conventional methods, therefore, tent fumigation was the selected method. The preferred fumigant, methyl bromide, was not selected because it posed a potential risk to the paintings due to its solvent action, the high relative humidity (up to 95%), which might cause formation of hydrobromic acid and a colour change in sensitive pigments. Hydrogen cyanide was dismissed for similar reasons. Sulphuryl fluoride was considered, but rejected because there was no registration in Norway, it has poor ovicidal activity and is expensive.

This was one of the first uses of magnesium phosphide formulated in a plastic matrix. This formulation does not liberate ammonia which can cause damage. Extensive laboratory trials using simulated ingredients used by the original artists established that phosphine had the lowest risk. Despite this, considerable time was spent covering all silver and gilt coatings to prevent exposure to phosphine.

Had methyl bromide been selected, 300 kg would have been required.

Phosphine has been accepted for many years as an alternative to methyl bromide for structural fumigations where prolonged exposure times are possible, there is no risk of damage, and appropriate precautions can be taken to minimise risk.

This technique is rarely used in the Northern Hemisphere for commercial locations because the required exposure time of 8 - 15 days is not acceptable. In the case of non-commercial structures, time is not a major problem, permitting the use of phosphine. Had there been commercial pressures and time restraints, phosphine would not have been considered.

A considerable amount of laboratory and site time was spent testing the pigments and developing methods to isolate the various gilt materials from the effects of phosphine. Those gilt and silver items which were movable, were removed from the church prior to the fumigation. Only after extensive trials did the fumigators feel confident to undertake this work.

The location of the churches presented a significant logistic problem: moving personnel and equipment to isolated parts of Norway. Treatments were time consuming as each building had to be completely wrapped in fumigation sheeting, and all sensitive materials in the churches had to be protected from phosphine.

The fumigations were very successful. The churches have been monitored since the fumigations and there have been no reports of any insect activity. The paintings and carvings show no signs of change or deterioration.

Sources:

Anon. 1985: Hausbockbekamfung in einer Stabkirche Debkmalpflege durch Begasung sichert schonende Behandlung. Holz-Zentralblatt, Stuttgart, p. 1020.

The fumigation of the three churches is recorded in a confidential Rentokil document "Preservation of Stave Churches Norway, August - September 1984."

5.0 DEVELOPING COUNTRY ISSUES

Executive Summary

Article 5 countries currently use about 18% of the global production of methyl bromide for agricultural use. Main uses are for soil fumigation (about 70% of Article 5 total) and disinfestation of durables (about 20%). The relative importance and dependence on methyl bromide varies widely between Article 5 countries.

Where methyl bromide is used for soil fumigation in Article 5 countries, it is principally for pest and disease control in the production and export of certain high value cash crops (e.g. tobacco, cut flowers, strawberries, vegetables). It is used particularly for fumigation of nursery and seed beds for these crops. Methyl bromide is not used during production of staple foodstuffs. Where used, the main application on durables is for the protection of local stocks of food grains and for disinfestation of imported and exported cereal grains.

Alternatives to methyl bromide in Article 5 countries and potential constraints on their use are the same as in developed countries, but their application is generally further constrained by the social conditions, level of infrastructure and other conditions typical of many Article 5 countries.

At present there is no single in-kind alternative for all, or even most, uses of methyl bromide in Article 5 countries. For some quarantine applications (e.g. certain berryfruit infested with thrips or aphids, certain unwashed root vegetables infested with soil pests) there are currently no technically feasible alternatives.

While it may be possible to use alternative chemicals and/or production methods, including Integrated Pest Management (IPM) strategies, to substitute for most of the pest control uses of methyl bromide, the varied and special conditions in Article 5 countries require that the alternatives be appropriately adapted to the climatic conditions, particular cropping techniques, resource availability and specific target pests. Different alternatives will have to be used for different crops, commodities and situations. This is likely to involve significant effort toward selecting appropriate alternatives, adaptive research, field testing, technology transfer, user education, institutional capacity building and training, among other factors. It is critical that those Article 5 countries which utilise methyl bromide receive technical and financial assistance in introducing or adapting alternative materials and methods to manage the pests currently controlled by methyl bromide.

The Committee noted that the specified incremental costs eligible for funding under the multilateral fund and items on the indicative list may need revision in order to accommodate the special needs associated with methyl bromide, if phase out is considered.

Potential trade restrictions relating to methyl bromide use are of great concern to those Article 5 countries dependent on certain important exports now produced with the aid of methyl bromide. Such restrictions, which could be applied by developed, importing countries and/or regions, as a result of their own or international restrictions on methyl bromide, are seen as an issue of substantial importance. They could nullify the effect of any grace period.

5.1 Introduction

This chapter of the MBTOC report presents an overview of the current uses of methyl bromide in Article 5 countries, and discussion on potential and existing alternatives to the use of this pesticide in regard to feasibility, potential problems (including user safety and environmental concerns), as well as other country-specific concerns. In addition, this chapter outlines the kinds of issues to be assessed in developing and appraising research and technology transfer projects for introducing or developing country-specific alternatives for Article 5 countries.

In light of possible future restrictions on methyl bromide, this chapter describes Article 5 country-specific issues with regard to the implementation of alternatives. In comparison to developed countries, Article 5 countries have, in general, characteristics that may affect the economic and technical feasibility of the implementation of alternatives to methyl bromide. Resources such as technological capacity and infrastructural attributes in Article 5 countries tend to be less developed. Article 5 countries may also have more urgent social needs and are more dependent on the agricultural sector than developed countries.

Several Article 5 countries have become dependent on the use of methyl bromide for some important aspects of their economies. Issues, such as short-term agricultural development, poverty, global inequalities, and external debts, are often closely linked to the revenue generated by the export of crops which have become dependent on methyl bromide, both for viability of production in economic terms, as well as for export quality. These issues should be considered carefully during any phase out of methyl bromide, especially as specific alternatives are introduced or developed and implemented in Article 5 countries.

In addition, in many Article 5 countries government regulatory and advisory staff are typically few in number, with technical assistance for pesticide use often provided mostly by pesticide manufacturers and distributors. Furthermore, since regulatory controls for pesticide use in Article 5 countries may often be inadequate, the implementation of chemical alternatives to methyl bromide will need to include provision for local extension services and training of local pest control personnel in the technology program so as to ensure safe and effective use. Implementation of non-chemical alternatives, some of which may require considerable skill for effective use, will also require good local services and training.

The financial mechanism of the Montreal Protocol makes explicit provision for the incremental costs associated with adoption of non-ozone depleting technologies in place of substances controlled under the Protocol. The fourth meeting of the Parties approved the indicative list of those incremental costs to be financed. However, this list will need modification to reflect the specific incremental costs of methyl bromide replacement, if phase out is agreed, as the present list is only relevant for substances of Annexes A, B, and C of the Protocol and the technologies relevant to these substances. The committee suggests the Parties prepare and approve the relevant additions to the indicative list if methyl bromide is further controlled and when considering extending these control measures to Article 5 countries.

There is concern that potential trade conditions which may be imposed by importing countries upon Article 5 countries that utilise methyl bromide in the production or disinfestation of export commodities may render a grace period ineffective. Furthermore, the international FAO Code of Conduct for Procedures of Pesticides states that pesticides which are severely restricted or prohibited in the producing country cannot be exported to developing countries. This could apply to methyl bromide in case of a ban in the developed countries or regions. Developed countries or regions may wish to consider adjusting their legislation in a manner which will enable Article 5 countries to use methyl bromide and to export commodities produced or treated with methyl bromide without restrictions during a grace period.

5.2 Methyl bromide use in Article 5 countries

Methyl bromide is a broad spectrum pesticide which is used as a fumigant in the control of insects, nematodes, weeds, pathogens, and rodents. Methyl bromide usage in developing countries in 1992 was about (18%) of global consumption of methyl bromide for agricultural and related uses. Breakdown of usage by Article 5 country is given in Table 5.1.

Table 5.1 Consumption of methyl bromide by some Article 5 countries (1992)

Territory	Country	MeBr consumption (t)	(% of Total)	
			Soil	Commodities
ASIA	Bangladesh	20		
	China	1,000		
	India	141	0%	100%
	Indonesia	260	0%	100%
	Iran (Islamic Republic of)	100		
	Jordan	900		
	Lebanon	30		
	Malaysia	69		
	Myanmar	100	0%	100%
	Pakistan	60		
	Philippines	70	50%	50%
	Republic of Korea	1,400		
	Saudia Arabia	100		
	Singapore	110	100%	0%
	Sri Lanka	6	0%	100%
	Syria	10		
	Thailand	1,200	5%	95%
	Turkey	800	100%	0%
	United Arab Emirates	50		
	Vietnam	100	0%	100%
SUBTOTAL		**6,526**		
CENTRAL AMERICA AND CARRIBEAN	Bahamas	2		
	Barbados	1		
	Costa Rica	400	100%	0%
	Cuba	300		
	Dominican Republic	40	100%	0%
	El Salvador	95		
	Guatemala	60	100%	0%
	Honduras	200	100%	0%
	Mexico	1,000		
	Trinidad	2		
SUBTOTAL		**2,100**		
SOUTH AMERICA	Argentina	400	100%	0%
	Brazil	1,400	90%	5%
	Chile	319	70%	30%
	Colombia	130		
	Ecuador	70	100%	0%
	Peru	20		
	Uruguay	20	100%	0%
	Venezuela	100	100%	0%
SUBTOTAL		**2,459**		

Table 5.1 (cont.) Consumption of methyl bromide by some Article 5 countries (1992)

Territory	Country	MeBr consumption (t)	(% of Total)	
			Soil	Commodities
AFRICA	Algeria	50	100%	0%
	Cameroon	60	100%	0%
	Cote d'Ivoire	70	50%	50%
	Egypt	750	70%	20%
	Ethiopia	1		
	Gabon	50	80%	20%
	Ghana	100	0%	10%
	Kenya	250	55%	20%
	Libyan Arab Jamahiriya	150		
	Malawi	207	90%	0%
	Morocco	450	80%	0%
	Mozambique	15		
	Namibia	2		
	Nigeria	40		
	Senegal	40		
	Tanzania (United Republic of)	20		
	Zambia	330	90%	10%
	Zimbabwe	660	80%	20%
SUBTOTAL		**3,245**		
EUROPE	Albania	40		
	Cyprus	100	100%	0%
	Malta	40	100%	0%
SUBTOTAL		**180**		
TOTAL		**14,510**		

Data source: Bromine Compounds Ltd. and MBTOC survey.

Notes:

(1) Commodity fumigation includes treatment of durables, perishables and structures.

(2) Usage of methyl bromide in Central and Southern Africa was considerably lower than normal in 1992 due to a very severe drought and reduced harvests. This may have not only affected the quantity used, but also the relative proportion used on soils and, particularly, on durables, particularly food grain stocks.

(3) Article 5 countries not shown in this table are assumed to have little or no consumption of methyl bromide.

Because of its relatively low price, and its physical and chemical properties, it is used under diverse geographical conditions found in Article 5 countries. This chemical is used primarily for soil treatment, durables fumigation and, to a lesser extent for perishables, and structural fumigation. Detailed data, obtained from 25 Article 5 countries, accounting for 7,728 tonnes of consumption of methyl bromide, showed a usage of 60, 30, 10 and 0.1% of reported methyl bromide usage for soil, durables, perishables and structural treatments. Less specific data from a wider range of Article 5 countries, showed 72% of usage on soils and 28% in enclosed spaces. Usage, in terms of weight, is not necessarily a direct reflection of the economic importance of methyl bromide in particular sectors.

Discrepancies were noted between different data sources with regard to consumption of methyl bromide by developing countries. Table 5.2 shows the tonnages for developing countries in three regions. A similar analysis for developing countries elsewhere cannot be presented as the data is not available in a suitable form. The MBTOC survey can be expected to give a lower estimate than the other sources as some users did not respond to the survey.

Table 5.2 Consumption of methyl bromide (t) in developing countries in three regions (1992)

	Data source		
Region[a]	BC[b]	MBGC[c]	MBTOC Survey
Africa	1594	996[d]	1463
"N. Africa"	1651	1363	1000
S. America	2459	2300	1252
TOTALS	**5704**	**4659**	**3715**

[a] Countries classified into regions according to MBGC system (Table 2.2).
[b] Bromine Compounds Ltd. data (used in Table 5.1).
[c] Methyl Bromide Global Coalition data (from Table 2.2).
[d] South Africa consumption (est. 701 t) subtracted from MBGC estimate.

In many, but not all Article 5 countries, little or no methyl bromide is used for the production of food for in-country consumption. None is used for production of staple foodstuffs.

Presently, there is no single alternative chemical treatment or combination of treatments that can substitute for methyl bromide in all of its many applications. However, a systems approach (IPM) using alternative chemicals, non-chemical measures and production methods may substitute for the pest control uses of methyl bromide in many situations.

The most critical use of this pesticide is on cash-crop exports (e.g. tobacco, cut flowers, some fruits and certain vegetables), which are important to the economies of many Article 5 countries. Often such treatment is part of preshipment or quarantine measures and is required as a condition of entry to the country to which the commodity is destined, usually a developed country. It is essential that alternatives to the use of methyl bromide for perishable commodities will not only control the target pest effectively, but also be accepted by the importing country as admissible treatments.

Agricultural systems which rely on methyl bromide are currently being developed and expanded in a number of Article 5 countries as one important method of producing certain high value crops for export. In addition, a significant portion of the population in several Article 5 countries (e.g. Kenya, Colombia, Zimbabwe) is employed in production of these high value crops.

Important specific Article 5 country uses include:

- Soil fumigation (nursery and seed bed) for production of certain export commodities to developed country markets. This may include vegetables, strawberries, cut flowers and tobacco, among other crops.
- Fumigation of some durable commodities (such as timber, tea, cocoa beans) for export. Methyl bromide is used primarily as a quarantine treatment specified by the importing country.
- Fumigation of perishable commodities (e.g. some fresh fruit, vegetables, cut flowers) for export to meet quarantine, phytosanitary, and commercial requirements of certain importing countries.
- Disinfestation of in-country food stocks, particularly cereal grains held in long-term storage and against the Larger grain borer in Africa.
- Specific treatments required by importing countries against pests of quarantine significance (e.g. Khapra beetle, African giant snail, Larger grain borer).
- Disinfestation of ships, aircraft, and other transport vehicles for rodent control or to prevent the cross-contamination of exports.
- Disinfestation of imported grain, notably as food aid. This may be in transit to a third country.

Potential alternatives in specific use areas are as described in other sections of this report. They include cultural practices, IPM, other pesticides, heat or cold treatments, controlled atmospheres, and irradiation. The choice of alternatives will be determined largely by the commodity tolerance and the target pest, and the potential success based upon research findings or experience elsewhere. Since many exported commodities are perishable, and will lose quality under prolonged storage, it is essential that an effective treatment be accomplished within a short period prior to shipment, as well as having a high degree of pest efficacy. Research needs to focus on specific cash-crop exports for each particular situation, commodity, and pest. Country-specific infrastructural limitations and needs should be defined and delineated early to assure lasting technology transfer.

5.3 Soil fumigation

In Article 5 countries, about 70% of the total imported methyl bromide is used for pre-plant soil fumigation, controlling soil-borne pests, such as diseases, nematodes and weeds. This pesticide is used particularly during nursery-bed preparation for some tobacco, flower, vegetable and strawberry seedling production. The chemical is also used to a limited amount to fumigate soil to control replant problems associated with perennial fruit trees such as apples, pears, citrus and guava, among others, as well as on established recreational areas, such as golf greens. In addition, a small amount, depending on the country, is used for general fumigation of fields for vegetable crops. Almost all methyl bromide use on soils is related to export crops, with very little (less than 2%) used for the production of food for in-country consumption, and none for production of staple foodstuffs.

5.3.1 Progress on development and adoption of alternatives to methyl bromide use in soil fumigation

There are several potential alternative chemicals, for example, dazomet, 1,3-dichloropropene, metam sodium, formalin, as well as well-known non-chemical techniques notably crop rotation and other cultural practices, and others such as biological control, and solarisation which are currently used in the developing countries to a limited extent to complement or replace methyl bromide. These alternative materials or technologies, however, may require substantial development and research to be cost-effective, available, and applicable to the special needs of Article 5 countries. In many cases, combinations of measures are likely to be required to control the range of pests now controlled using methyl bromide.

Many of the potential chemical alternatives to methyl bromide are potentially hazardous to humans and the environment, and may require specific training and regulation to ensure safe, effective use. It should be noted that methyl bromide is, itself, also potentially hazardous to humans and the local environment, and also requires skilled application and substantial precautions for safe, effective use. Lack of appropriate skills is a general constraint to use of both methyl bromide and alternatives in many Article 5 countries.

5.4 Fumigation of durables

Methyl bromide is used in some situations in Article 5 countries to fumigate stored commodities such as cereals/grains, seeds, dried spices, wood, timber and wood products, bamboo ware, tapioca, silos, warehouses, and containers. Commodities may also be fumigated with methyl bromide prior to import or export, as a quarantine requirement.

In eastern and southern Africa, methyl bromide is used in the fumigation of durable commodities such as dried spices, timber and wood products, coffee, and grain. In the Latin American countries of Brazil, Mexico, Chile, Argentina, Colombia, El Salvador and Uruguay, methyl bromide finds some use for fumigation of durables such as coffee, rice, cotton, maize, wheat, beans, peanuts, soya bean, sorghum and timber.

On an annual basis, of the total quantity of methyl bromide used in Article 5 countries, about 20% is utilised for the fumigation of durables. Although the total quantities of methyl bromide used by the developing countries for durable fumigation is generally low, its use is of importance on specific commodities for certain economic sectors and foreign exchange earnings of particular Article 5 countries. For example, in 1988, Indonesia exported timber to Japan, Singapore, and Taiwan valued at US$753 million, a large proportion of which was treated with methyl bromide, primarily by the importing countries.

In some circumstances, elimination of methyl bromide will increase jobs and value added in developing countries. For example, the timber exported from Indonesia that currently require methyl bromide treatment is shipped largely as whole logs. They are de-barked, sawed, dried and worked into valuable forest products in the importing country. However, logs could be debarked and cut in Indonesia and treated with either heat or pesticides as needed.

As most developing countries are located in tropical or sub-tropical climatic zones, pests and diseases can pose a greater threat to durable commodities than in temperate regions. This can exacerbate the pest problems (insects and rodents) which can cause substantial losses of durables either in storage or during export. Under these circumstances, fumigation with methyl bromide is one process which has been found effective in preventing losses.

5.4.1 Progress on development and adoption of alternatives to methyl bromide in durable commodity pest control

Phosphine is an effective alternative fumigant which, when used and applied properly, can directly substitute for methyl bromide in many durable commodity applications. In most Article 5 countries it is the fumigant of choice for protection of stored grains and tobacco. Methyl bromide is used largely because of a tradition of effective use, not because of specific advantages of the material. While phosphine can be used as an alternative to existing uses of methyl bromide, there are constraints, which need to be considered:

- Insect pest resistance has been identified in several Article 5 countries.
- Phosphine requires a longer fumigation period than with methyl bromide for full effectiveness. This may slow importation or exportation processes to a level where it may be difficult to accommodate logistically.
- The potential of fire hazard during application if the material is handled improperly or carelessly.
- Currently available formulations of phosphine are not suitable for very dry conditions, the gas taking much longer to be released than normally. It is not generally recommended where grain moistures are below 9%.

A systems approach or other single technologies are currently used in many Article 5 countries for disinfestation of durables where methyl bromide could be used. For instance, fumigation of rice with carbon dioxide is routinely used in Indonesia on a large scale for protection of stored rice and has been used experimentally in Papua New Guinea for protection of stored coffee. Controlled atmosphere treatments have been used to replace methyl bromide for disinfesting coffee and cocoa beans.

Available alternative technologies for durables include sulphuryl fluoride (for wood), carbon dioxide, hot air treatments, steam treatments, hot water dips, hermetically sealed storage, controlled atmospheres, irradiation and combined treatments such as protein coating with steam (for spices), and vacuum steam flow processes (for leaf tobacco). However, these technologies may be appropriate for some commodities only and may require additional research and capital to adequately replace methyl bromide where rapid disinfestation is needed. Additionally, they may not have local registration for use.

5.5 Fumigation of perishables

Methyl bromide is sometimes used to fumigate perishable agricultural products, such as cut flowers, stem cuttings, bud-wood, rooted plants, bulbs, corms, rhizomes, fresh fruits, including grapes, bananas, and vegetables prior to export. This is a critical area of use to some Article 5 countries, with an estimated annual usage of about 7% (667 tonnes) of total. The majority of this usage is due to quarantine and other phytosanitary requirements of the importing countries.

Examples of perishable commodities, some of which are currently treated with methyl bromide, and their economic importance include:

- cut flowers in Kenya, which accounts for 13% of the total foreign exchange earning (US$42 million in 1992);
- cut flowers, fruit and vegetables from Colombia which between 1988 and 1992, provided 3.9% of the total foreign exchange earnings;

- cut flowers in Thailand, which accounts for an annual US$20 million;
- grapes exported from Chile to USA which in 1993 accounted for 3% of total exports (value US$293 million).

Note that the need for treatment is usually driven by the requirements of the importing country and the prevalence of the pests. Only a proportion of this trade (but all Chilean grapes to USA) is treated currently with methyl bromide.

5.5.1 Progress on development and adoption of alternatives to methyl bromide in perishable fumigation

Alternative quarantine treatments or procedures already approved by certain countries include pre-shipment inspection, pest-free zones or periods, cultural practices, cold and/or heat treatments, controlled atmospheres, physical removal of pests or soil. For example, cold treatments are used for apples from Chile, Jordan, Mexico, and Uruguay to the USA, for plums and apricots from Morocco to the USA; and for kiwifruit from Chile to Japan. Heat treatments are used to disinfest papaya, mango, citrus, eggplant, zucchini, squash and bell peppers, and could be developed for a wide range of perishables. In some cases combined treatments are necessary, such as soapy water with wax for cherimoya from Chile, and vapour heat with cold treatment for lychee from Taiwan.

Each treatment is dependent upon the commodity, the target pest, and the geographical area. Some of these treatments are already in operation to a limited extent in specific countries. Limitations and constraints can include capital costs, operational costs, lack of country-specific research, technical capabilities and especially, quarantine acceptance by the importing countries, and inconsistent results of a particular alternate treatment. However, some alternative treatments may give improved retention of quality in transport and storage compared with methyl bromide use.

5.6 Structural fumigation

Small quantities of methyl bromide, less than 1% of Article 5 country use, are used in Article 5 countries for empty structures, including ships, warehouses, flour mills, aircraft. Fumigation of ships and aircraft is usually in compliance of quarantine requirements.

5.6.1 Progress on development and adoption of alternatives to methyl bromide for structural fumigation

Phosphine is the principal alternative chemical that is available for structural fumigation. However, the disadvantage of phosphine in structural fumigation is that it reacts with and corrodes copper materials and similar alloys which may be found in machinery, and ancillary electrical equipment. Other limitations have already been discussed in the Durables section of this chapter.

Other chemical potential alternatives for structural pest control include fumigants such as sulphuryl fluoride (not recommended for structures containing foodstuffs) and hydrogen cyanide (not very penetrative, fire hazard). Pesticides such as chlorpyrifos-methyl, pirimiphos-methyl, fenitrothion, malathion, and other contact insecticides can be utilised, where approved.

5.7 Recycling, Recovery and Reclamation

Presently the Article 5 countries do not recycle, recover or reclaim methyl bromide. Once the technology is developed and feasible, the Article 5 countries are likely to benefit by adoption of these technologies in order to recover methyl bromide applied to fumigation chambers, structures and buildings. Some Article 5 countries are currently investigating application of this technology (e.g. Chile). Better containment and recycling of methyl bromide may improve the reliability of fumigation and thus help to maintain and expand export markets. However, most recovery technologies, and all the recycling technologies, are likely to have high capital and running costs. They may also be energy intensive. Many would require a level of technical expertise not normally found currently at fumigation facilities.

5.8 Replacement of methyl bromide

The complete replacement of methyl bromide will involve not only site-specific agricultural research, but also social and economic processes such as:

- The creation of awareness in regard to the Montreal Protocol and ensuring that adequate technical information is made available at all relevant levels.

- The determination of the capacity of various developing countries in terms of technological capabilities, manpower resource base, and the availability of funds to implement alternative pest control methods.

- The development and production of training and public information materials for distribution to the relevant authorities and personnel such as technical staff, local farmers, and the public sector.

- The implementation of sound programs to ensure a quick field adoption of alternatives.

Among the technical strategies necessary for developing alternatives to methyl bromide use, there is a need for the following specific research priorities:

- implementation of IPM practices, which include non-chemical technologies (e.g. using healthy stocks for propagation, preventative - quarantine, crop rotation, biological control, etc.), and including chemical pesticides when needed;

- research to find, adapt and implement alternatives that are effective, environmentally sound, easy to apply, safe to users and affordable, and specific to local conditions, crops and target pests;

- technology transfer to enable developing countries to evaluate and implement the use of alternatives;

- training of local technical staff as part of the process of technology transfer.

5.9 Conclusion

Methyl bromide is currently used in many Article 5 countries for certain economically important products of agriculture. It is important that alternatives to methyl bromide for use in Article 5 countries allow the continued economic gains from agricultural and horticultural production. Article 5 countries using methyl bromide will require some assistance to implement alternative pest control methods which are affordable, environmentally sound, and safe to users.

Alternatives need to be country-specific, crop-specific, and pest-specific, and will require substantial programs involving research, technology transfer, training and infrastructure strengthening.

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